Escola d'Enginyeria de Telecomunicació i Aeroespacial de Castelldefels
UNIVERSITAT POLITÈCNICA DE CATALUNYA

# TREBALL FINAL DE GRAU

**TÍTOL DEL TFG: DESIGN OF A PLANETARY AEROBOT**

**TITULACIÓ: Grau en Enginyeria d'Aeronavegació**

**AUTOR: Álvaro Boix Candil**

**DIRECTOR: Jordi Gutiérrez Cabello i Pilar Gil Pons**

**DATA: 15 de juliol del 2018**

**Títol:** Disseny d'un aerobot planetari

**Autor:** Álvaro Boix Candil

**Director:** Jordi Gutiérrez Cabello i Pilar Gil Pons

**Data:** 15 de juliol del 2018

## Resum


L'objectiu principal d'aquest treball és dissenyar un vehicle aeri que pugui contribuir en la investigació planetària d'una manera més òptima que les missions actuals. S'ha decidit que un "aerobot", el qual consisteix en un globus i una instrumentació científica (també conegut com a "payload") que penja d'aquest globus, seria l'opció més apropiada per la seva millor resolució que els satèl·lits i la seva millor mobilitat que els rovers. Aquest globus s'emplena d'un gas flotant que ha de ser més lleuger que l'aire atmosfèric per fer possible el vol del globus. En aquest projecte es fa un estudi de les diferents opcions d'aerobots i de gas flotant que podrien ser utilitzats per aquesta missió.

En termes més específics, l'aerobot escollit és un Super Pressure Balloon d'heli fet de LLDPE, el qual té un diferencial de pressió positiu entre la pressió interna i atmosfèrica, per tant, la seva altitud de vol es mantindria constant durant el seu vol. La grandària i la massa del globus, les propietats internes, la velocitat vertical durant l'ascens i la durabilitat del globus són algunes de les característiques de l'aerobot que han estat calculades en aquest treball. Aquesta durabilitat del globus està determinada per les característiques de filtratge del film i la difusió de l'heli.

A més, s'ha fet un estudi de Mart per aplicar el disseny de l'aerobot a les singulars condicions marcianes. S'ha fixat un model d'atmosfera per Mart, el Viking-Pathfinder, a partir del qual s'han determinat les característiques del globus.

També, s'han exposat diferents sistemes extres que podrien millorar el rendiment de l'aerobot, augmentant la seva capacitat d'exploració o la seva durabilitat.

Finalment, s'ha conclòs que un aerobot planetari podria millorar en gran mesura l'exploració actual de cossos del sistema solar amb atmosfera, ja que es demostra que el càlcul del seu disseny és possible. No obstant això, es necessita una gran millora i treball futur en el material de la coberta del globus i en la tecnologia de la flotabilitat d'un globus en altres atmosferes per fer aquesta missió viable.

**Title:** Design of a planetary aerobot

**Author:** Álvaro Boix Candil

**Director:** Jordi Gutiérrez Cabello and Pilar Gil Pons

**Date:** July 15 th 2018

## Overview


The main objective of this project is to design an aerial vehicle which can contribute in planetary research in a more optimal way than the current missions. It has been decided that an aerobot, which consists in a balloon and scientific instrumentation (also known as payload) hanging from this balloon, would be a suitable option due to its better resolution than orbiters and its better mobility than rovers. This balloon is filled with a buoyant gas that must be lighter than the atmospheric air in order to make possible the balloon flight. In this project there is a study of the different aerobot and buoyant gas options that could be employed for this mission.

In more specific terms, the chosen aerobot is a helium Super Pressure Balloon made of LLDPE, which has a positive pressure differential pressure between the internal and atmospheric pressure, so its float altitude would keep constant along its flight. The balloon size and mass, internal properties, vertical speed during ascension and lifetime of the balloon are some of the aerobot characteristics that have been computed in this project. This balloon endurance is determined by the film leakage features and helium diffusion.

Moreover, a study of Mars has also been performed in order to apply the design of the aerobot to the singular Martian conditions. An atmosphere model for Mars has been settled, the Viking-Pathfinder, from which the balloon characteristics have been determined.

Furthermore, there have been exposed different extra systems that could improve the performance of the aerobot, increasing its exploration capabilities or its endurance.

Finally, it has been concluded that a planetary aerobot is a system that would improve to a large extent the current exploration of solar system bodies with a substantial atmosphere due to it is proved that its design is possible. However, it is also needed a great improvement and future work at the balloon envelope materials and buoyancy technology of a balloon in foreign atmospheres to make it a feasible mission.

# INDEX

# INTRODUCTION

Planetary exploration has always been located in the frontline of space research. The principal goal of the human race has been the study of the different components of the Solar System planets and moons or even the possible present or past existence of life, not only to discover new organisms, but also to understand the past, present and future of our planet.

The main objective of this project is to design an aerial vehicle which can contribute to this research in a more efficient way than current missions. It has been decided that an aerobot flying at an intermediate float altitude would be the most suitable option due to its better resolution than the orbiters and its better mobility than the rovers. An aerobot consists in a spherical balloon and scientific instrumentation, also known as scientific payload, hanging from this balloon thanks to a long rope. This balloon is filled with a buoyant gas that must be lighter than the atmospheric air in order to make possible the balloon flight. In this project there is a study of the different balloon systems that have been already designed and lifting gas options that could be employed for this mission.

The chosen aerobot is a Super Pressure Balloon (SPB), which has a positive pressure differential pressure between the internal and external pressure, so its float altitude would keep constant along its flight. This SPB is filled with helium as its buoyant gas, which is one of the lightest ones, and made of LLDPE (Linear Low Density Polyethylene), which has a great fracture toughness and resistance to leaking holes. The balloon volume, internal pressure, density and temperature, helium and envelope masses, vertical speed during ascension and endurance of the balloon are some of the characteristics of the aerobot that have been computed in this project. This balloon endurance is determined by the leakage features of the LLDPE film and helium diffusion, which depends on the temperature and pressure of the gas.

Moreover, a study of Mars has also been performed in order to apply the design of the aerobot to Martian conditions, taking into account its surface, topography, atmosphere composition, wind, weather and diurnal cycles of Mars. An atmosphere model for Mars has been used, the Viking-Pathfinder model, based on the measures taken by these two spacecrafts, from which the balloon characteristics have been determined.

Furthermore, there is a description of different extra systems that could improve the performance of the aerobot, increasing its exploration capabilities or its endurance. These systems include an electric engine that makes possible some navigation capabilities or a gas collector that returns into the balloon envelope the leaked gas.

Finally, it has been concluded that a planetary aerobot would improve to a large extent the current capabilities of the exploration of Mars (or, in fact, other interesting Solar System bodies with atmosphere. However, it would necessary a substantial improvement on the balloon envelope materials and buoyancy technology to make it a feasible mission.

# CHAPTER 1. PLANETARY AEROBOT

## 1.1. Advantages and limitations

No engineering system can claim to give only advantages without any kind of weaknesses. We devote a few pages to analyse both advantages and disadvantages of this kind of systems.

### 1.1.1. Advantages

Aerobots allow many advantages that make them suitable, even unique, for some missions on solar system bodies with a substantial atmosphere. In what follows, we will summarily analyse their main advantages.

#### *1.1.1.1. Simple and cheaper technology*

An aerobot is composed by a balloon of a polymer envelope film with buoyant gas inside it, a payload under the balloon and a system of ducts and ropes to connect both parts. On the other hand an aircraft has a large number of systems and subsystems, even the smallest ones, which make them much more complex. The most significant subsystems compared to an aerobot would be: the fuel system (including the storage, the supply and the engine itself), its mechanism to generate thrust and the lifting system, which is a difficult one due to the great differences between Earth's atmospheres and the ones on other Solar System bodies.

**Fig. 1.1** Mars aerobot concept

In particular, the low density of Martian atmosphere would call for significantly larger areas for the wings. Finally, a system like a plane requires an autonomous control system, as the delay in the communication with the Earth makes remote control unsuitable. All this implies that designing and building an aerobot requires less work, less time, fewer resources and a smaller economical effort.

#### *1.1.1.2. Better resolution at high altitudes*

Aerobots can easily achieve greater altitudes than planes, but stay far closer than satellites. We can decide the flying altitude of the aerobot, provided a more or less stable atmosphere. As stated before, the flight altitude includes very high levels that cannot be reached by other aeronautic systems as aircrafts, where the very low air density limits their ceiling.

From the other side, they would be much closer to the surface than orbital systems like satellites or other spacecrafts, which could have difficulties to analyse the planet because of their altitude and speed (but this crucially depends on the payload, as very high resolution data are routinely gathered nowadays by orbital missions around Mars). An accurate study of a specific area of the planet could be better performed by an aerobot.

### 1.1.2. Limitations

#### *1.1.2.1. Low endurance*

Superpressure balloons are the type of aerobot which are designed to reach the longest endurance, about 100 days. Unfortunately, nowadays the longest journey on Earth has been of 54 days. The main reason is that the polyethylene film of the balloon has unavoidable microscopic holes and helium molecules are so small that they easily leak through them, gradually deflating the balloon. Furthermore, the film is not very resistant to blows and strong fluctuations, so many disturbances can create more of these holes or make the previous ones bigger.

#### *1.1.2.2. Instability*

The buoyancy of an aerobot depends on the difference of density between the internal and external gas. This means that the altitude depends on atmospheric temperature, which varies along the day and the journey, and volume, which varies because of the leaking of the gas. Moreover, atmospheric disturbances can also change the altitude, the horizontal position, the heading or the speed of the balloon. These facts imply that an aerobot could be unstable in some cases and has severe control limitations.

#### *1.1.2.3. Limited speed and guidance*

The speed and track of the balloon is determined by the atmospheric wind because there are neither engines nor fins to guide the balloon. This makes difficult to cover wide areas and limits its exploration capability. However, there are other possibilities to compensate this. The most useful ones would be attaching an actuator like a thruster, with the inconvenience of the needing of fuel, or including a little electric engine which works thanks to solar panels attached to the balloon or to nuclear batteries or an RTG, with the inconvenience of needing solar energy or batteries as well as the large mass associated to nuclear energy sources. This could also help with the previous inconvenience of instability.

Nevertheless, its exploration range is by far larger than the rovers' ones, and kits endurance is very likely much longer than aircraft's.

#### *1.1.2.4. Limited payload*

In an aerobot system, the proportion of payload mass compared to the total mass is really limited due to the need of a big balloon volume to reach a high altitude with a minimum payload. However, the same can be said about for aircraft-based systems.

#### *1.1.2.5. Limited bit rate*

The mission of a planetary aerobot is to provide scientific information by exploring the planet. This information should be sent to Earth with the highest possible transfer data speed, which is determined by the bit rate. This is not a serious problem if the aerobot is supplied with solar energy, but there is a limitation in this bit rate if the aerobot is at the dark side of the planet or it is in a faraway object (like Titan, which also has a continuous cloud cover). Batteries or an RTG could also be a solution in the cases of distant planets.

In all cases, as the aerobot cannot control its orientation, the antenna should be omnidirectional, and then it would be mandatory to use some kind of orbit relay system, as is being done for some missions taking advantage of the flotilla of satellites orbiting Mars.

## 1.2. Classification of aerobots

Through history of ballooning, there have been a great variety of balloon systems, depending on the conditions required. These conditions include many factors as its buoyant gas, its material, its payload, the floating altitude or the duration of the flight.

### 1.2.1. Types of balloon system

The system used to perform the mission of this project is usually called LDB (Long Duration Balloon) or HAB (High-Altitude Balloon). These names give two of the previous conditions: it is a flight with a high ceiling altitude that has a long endurance. In order to achieve successfully these requirements the balloon must have a low mass due to the very low air density at high altitudes, and yet a strong material is also required to prolong the lifetime of the system.

Based on these demands, there are only two types of balloon systems that can be used for this kind of mission: Zero Pressure Balloons (ZPB) and Super Pressure Balloons (SPB).

#### *1.2.1.1. Zero pressure balloon (ZPB)*

The main characteristic of the Zero Pressure Balloon is, as its name says, that there is no difference between the internal pressure of the balloon and the external atmospheric pressure. Thanks to this fact, there is no need for a strong and thick material for the film (approximately 20 micrometers), so the balloon cover mass is reduced (see [1]).

**Fig. 1.2** NASA Zero pressure balloon

This kind of balloon has a valve on the top of its structure connected to a pipe which supplies the buoyant gas. It is partially filled on ground and then, as it rises, the gas spreads over the entire balloon from the top downward.

On the bottom, there is a vent which communicates with the exterior environment. Due to this aperture to the atmosphere, the internal pressure equals the external one. The excess buoyant gas is vented off by this duct when the float altitude is reached, so the balloon stops ascending and flies at a constant altitude.

The balloon maintains a constant altitude until there is a change in the environment temperature. The most significant case is when the sunset comes and the solar radiation energy disappears. At this moment, the lifting gas cools down and, consequently, it shrinks; then, a balloon on Earth's atmosphere descends approximately 1000 m or 2000 m to a lower float altitude.

In order to compensate this descent, some ballast material is usually released to reduce the dry mass of the system. This released ballast amounts in general to about an 8% of the total mass per day. In consequence, when the sun appears again, the total mass is reduced so the float altitude now is higher. Now there is again excess buoyant gas and some of it must be dumped.

This cycle is repeated every day/night cycle, so the lifetime of the balloon system is limited by the available ballast and the quantity of buoyant gas. As a result of this sequence of events, the endurance of this type of balloon system is usually from 7 to 15 days. Adding the problem of maintaining a constant floating altitude, this balloon system is not an optimal option for the mission of this project on grounds of endurance and complexity.

#### *1.2.1.2. Superpressure balloon (SPB)*

The principal difference between the SPB and the ZPB is that in the Super Pressure case the internal pressure is greater than the external one, so there is a positive pressure difference. This implies that now, contrary to the ZPB, the system needs a stronger and thicker film, so the dry mass now is higher. The material used is usually a co-extruded Linear Low Density PolyEthylene (LLDPE) film of 38.1 micrometers thick, which means almost twice the value for the ZPB (see [2]).

This system includes also a valve on the apex of the shell, where the buoyant gas is introduced into it. The balloon is partly inflated on ground too, so the gas is expanded inside as it ascends until it fills the whole volume.

In the case of the SPB, there is no vent connected to the outside, and so, when the balloon reaches the float altitude, the excess gas that generated the lifting force during the ascent does not exhaust through any duct. Instead of this, it has the purpose of pressurizing the inside of the shell and producing the positive pressure difference that characterizes the SPB. This pressure difference is usually about 300 Pa on Earth.

The positive internal pressure difference substitutes the method of releasing ballast in order to maintain the float altitude. Although it is not a large value, this pressure difference is enough to keep the balloon flying at the same altitude during the day/night cycles with the same volume. This means that the SPB offers a better stability than the ZPB.

**Fig. 1.3** NASA Super pressure balloon

Contrary to the ZPB, the endurance of the SPB is not determined by the mass of ballast or the gas exhausted because of the diurnal cycle. Now, the SPB endurance is limited by the diffusion and leakage of the buoyant gas through the balloon film. This is obviously a hugely reduced gas loss, so the durability is notably enlarged, even managing to last theoretically up to 100 days. Nevertheless, the longest flight of a SPB on Earth has been of 54 days due to unexpected atmospheric conditions that caused many holes which speeded up the leakage of the gas.

Analysing all the advantages and drawbacks of the two balloon systems, we conclude that a Super Pressure Balloon is the optimal option in order to accomplish the mission of this project, mainly due to its great endurance.

### 1.2.2. Types of buoyant gases

As important as the technology for the kind of balloon used, buoyant gases are one of the main decisions to be taken on the design of this mission. Table 1.1. shows the most important properties of a buoyant gas are shown, namely its density and its molar mass.

**Table 1.1.** Possible buoyant gas characteristics

| GAS | DENSITY STP ($kg/m^3$) | MOLAR MASS (g/mol) |
|---|---|---|
| Hydrogen ($H_2$) | 0.0899 | 2.016 |
| Helium (He) | 0.178 | 4.003 |
| Air ($N_2$+$O_2$+Ar) | 1.293 | 28.96 |
| Methane ($CH_4$) | 0.717 | 16.04 |

The density is measured in STP (Standard Temperature and Pressure) conditions, where temperature is 0ºC and pressure is $10^5$ Pa. These are very different conditions from Mars' atmosphere, but the table is useful in order to compare the different gases at the same conditions.

Hydrogen, helium and hot air are the most characteristic and most used buoyant gases, but there are other gases or methods that must be mentioned in order to consider all the possibilities.

#### *1.2.2.1. Hydrogen*

Its best characteristic is that it is the lightest existing gas. Although molecules of hydrogen are diatomic as a gas, they are two times lighter than helium, which is the second lightest gas. Moreover, hydrogen is easy to obtain by means of simple chemical reactions, and so it is not expensive.

Due to these advantages, hydrogen was the first buoyant gas which substituted hot air in the early balloons until the accidents that happened during the decades of 1910s and 1920s. The LZ-129 Hindenburg disaster in 1937, where 35 people were killed because the airship caught fire and was destroyed, marked the end of the use of the hydrogen as a lifting gas in balloons.

The accidents that have just been mentioned were caused by the most remarkable disadvantage of hydrogen, its high flammability. It burns when it is mixed with air at concentrations of more than 4%. Besides, its autoignition temperature is also about 500ºC. These facts difficult considerably the safety of an aerobot during launch procedures on Earth, but not in Mars where the atmosphere is almost devoid of free oxygen (as are the rest of the atmospheres found on the Solar System bodies other than Earth).

Furthermore, hydrogen molecule is the lightest and smallest one. As a consequence, hydrogen is easily diffused through many materials, which implies that the endurance of the balloon is limited by this leakage factor. . It is an essential aspect to be considered when buoyant gases are compared in order to design the balloon system.

#### 1.2.2.2. *Helium*

As was previously shown in Table 1.1., helium is the second lightest gas, which makes it almost as attractive as hydrogen. However, in contrast to hydrogen, helium is an inert gas, so it is neither flammable nor toxic, and it becomes a better option as a lifting gas for an aerobot, especially when the safety procedures during operations on the laboratory and during the launch are taken into account.

Moreover, although helium is twice heavier than hydrogen gas molecules, buoyancy depends on the density difference between the environment (air) and the buoyant gas. As the difference between air and helium densities is only an 8% higher than the one between air and hydrogen, helium provides about the 92% of the lifting power of hydrogen. This means that the difference between these two gases is not as large as it could seem analysing only their molecular weights.

Unfortunately, helium has two disadvantages. As helium is a light gas like hydrogen, it is also easily diffused through many materials. In order to counteract this, balloon films are made of plastics as Mylar or polyethylene by-products, which offer great resistance to the leakage factor of these gases in order to maximize the life of the aerobot.

The other inconvenient is that helium is scarce on Earth although it is so common in the universe. Until the twentieth century there were not gas wells in order to make helium commercially viable. Nevertheless, these gas wells are so limited that it has always been an expensive gas. All this makes helium a non-renewable resource unlike hydrogen, water or air.

**Fig. 1.4** Helium balloon tests at the Jet Propulsion Laboratory (JPL)

Taking all these factors into account, nowadays most of the balloon systems use helium as their buoyant gas.

#### *1.2.2.3. Hot air*

Air is not in itself a type of lifting gas, but a homogeneous mixture of several different gases. As is well-known, air is composed by a 78% of nitrogen, 21% of oxygen, 0.9% of argon and a 0.1% of other gases. Obviously, this mixture implies that a molecule of air is bigger than hydrogen molecules and helium atoms, so it is not so easily leaked.

Although air is relatively dense, the Ideal gas law, it is known that if air is heated, its density is lowered. Then buoyancy is generated due to the difference between the hot air inside the balloon and the air of the outside, which is obviously colder. The inconvenient of this is that a heating source is required, so it must be isolated from the rest of the aerobot. Furthermore, the heating source implies the need of an energy release and, consequently, the need of an energy source. This could limit the endurance of the system.

Nowadays, using air may seem a useless method, but it was used in the first manned balloon flight by the Montgolfière brothers in 1783, and even previously by the Chinese, who brought the primitive balloon technology to the western world. Obviously, the main advantage of using air is its availability.

Hot air balloons have mostly been replaced by other gas balloon technologies. However, it is still used for recreational ballooning. However, in Mars hot air balloons could be used if a suitable energy source is used (for example, by means of a black balloon that could be heated by the Sun).

#### *1.2.2.4. Methane*

It is lighter than air and, due to its larger size, its molecules are not so easily leaked as those of hydrogen or helium. So methane is used when a great lift is not necessary or when it is difficult to obtain hydrogen or helium.

A balloon in Titan could be a good example because it has a high density atmosphere (97% of which is composed of nitrogen) and it has a methane-rich surface, so it would be relatively easy to acquire it.

#### *1.2.2.5. Vacuum*

It is impossible to create a pure vacuum airship, so the closest option could be generating a near-vacuum environment, where density would be almost zero.

Theoretically, a vacuum “balloon” generates a 7% more lift force than hydrogen and a 14% more than helium.

The largely practical problem with this technology is that the pressure difference between the inside of the airship and the atmosphere is so enormous, that a strong material is needed in order to support this force. Unfortunately, nowadays there is no material that can accomplish these conditions without having a huge weight and then the buoyancy is not large enough for the system to float.

## 1.3. Balloon physics

After an extensive analysis of the different options that can be used in a planetary aerobot mission, it seems clear that the best option for this project in a general case is a Super Pressure Balloon filled with helium as the buoyant gas (hydrogen would also be a very good solution if we do not take into account operating difficulties while the balloon is still on Earth).

From here on, these two factors are the two most significant conditions which are going to determine the physics of the aerobot. Below, the procedure of the required computations is shown.

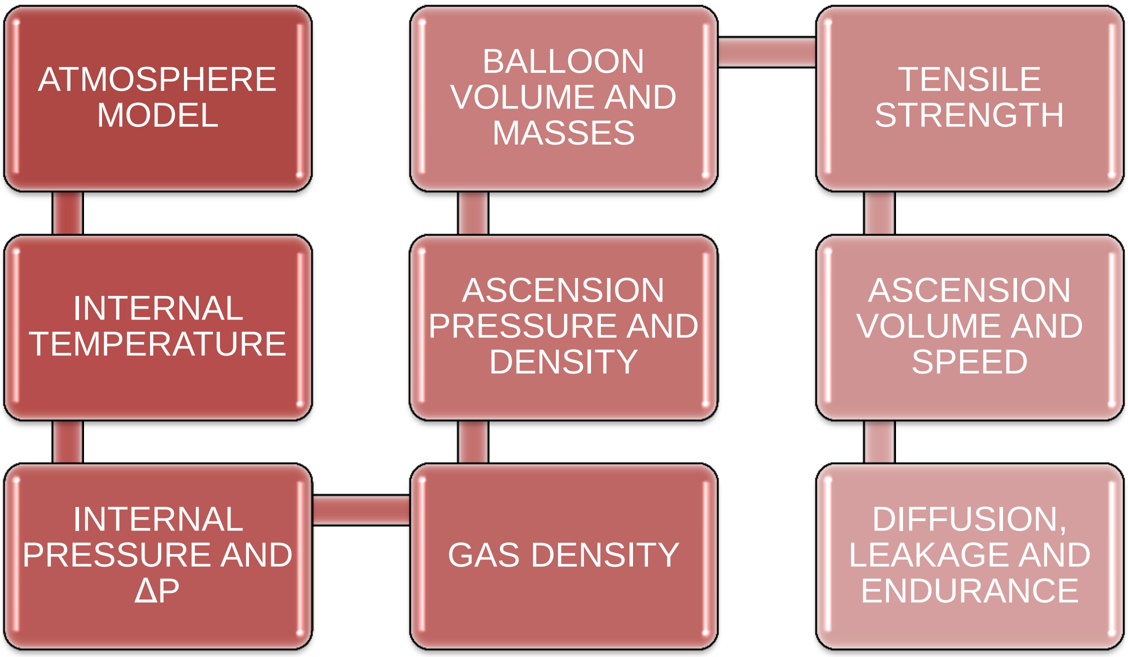



**Fig. 1.5** Computation procedure flux diagram

### 1.3.1. Atmosphere model

All the balloon parameters are accountable to the conditions of the atmosphere of the selected planet, in our case, Mars.

The atmospheric conditions that determine to the aerobot characteristics are pressure, temperature, environment density and gravitational force. Pressure, temperature and density are correlated between them by means of the equation of state and vary depending on the altitude and the time of day.

Their dependence is shown in the equation of state of an ideal gas,

$$P = \rho \cdot R_{gas} \cdot T \quad \textbf{(1.1)}$$

where $P$ is the pressure, $T$ is the absolute temperature, $\rho$ is the density and $R_{gas}$ is the gas constant (the ideal gas constant divided by the molecular mass of the specific gas, or mixture gases, forming the atmosphere).

In order to compute the gravitational force at a specific altitude, it is only necessary to know the gravity at sea level (or at the datum), the radius of the planet and the altitude of the balloon. This calculation is made by relating the gravitational force on the surface and the gravity at a given altitude as is shown below:

$$g(h) = g_o \cdot \left(\frac{R_P}{R_P+h}\right)^2 \quad \textbf{(1.2)}$$

Here, $g(h)$ is the gravitational force at altitude $h$, $g_o$ is the gravity at sea level and $R_p$ is the radius of the planet.

From this information, the planets have many atmospheric models that provide different types of data from which it is possible to generate a profile for the altitudes required (from 0 m to the desired float altitude of the balloon) of the four main parameters of an atmosphere (temperature, pressure, density and gravity).

For example, NASA has a specific method for Earth called the Earth Atmosphere Model (see [3]). The model for the Martian atmosphere will be discussed in section 2.1.2. There are different expressions and coefficients for the three stages that depend only on the gravitational force and the altitude. Then, thanks to the Ideal Gas Law, it is possible to determine the air density.

### 1.3.2. Gas temperature

Now there is a profile for the atmospheric pressure, temperature, density and gravitational force from sea level to the altitude at which the balloon is required to float in equilibrium. From the given profile of the atmospheric temperature, it is possible to calculate the first characteristic of the balloon: its internal temperature at every altitude.

A Super Pressure Balloon needs a high internal pressure in order to acquire a positive differential pressure, so the Ideal Gas Law demonstrates that the objective is to achieve the highest possible internal temperature. The expression to compute the gas temperature is the Thermal Balance Equation, which equals the energy radiative and the energy absorbed by the balloon:

$$S_{cover} \cdot \varepsilon \cdot \sigma \cdot \left({T_{gas}}^4 - {T_{out}}^4\right) = \alpha \cdot A_{cs} \cdot (J_{sun} + a \cdot J_{sun}) + A_{cs} \cdot \varepsilon \cdot J_{planet} \qquad \textbf{(1.3)}$$

$$T_{gas} = \sqrt[4]{\frac{\alpha \cdot (J_{sun} + a \cdot J_{sun}) + \varepsilon \cdot J_{planet}}{4 \cdot \varepsilon \cdot \sigma} + {T_{out}}^4} \qquad \textbf{(1.4)}$$

Here $S_{cover}$ is the surface of the balloon shell, which is considered as a sphere, $A_{cs}$ is its cross section, $T$ the temperatures inside and outside the balloon, $\alpha$ the absorptivity of visible radiation of the balloon film, $\varepsilon$ the emissivity in the infrared radiation of the film, $\sigma$ the Stefan-Boltzmann constant, $a$ the albedo of the planet and the $J$ are the radiated energy fluxes of the Sun and the planet in W/m$^2$.

The absorptivity and the emissivity are parameters which depend on the material of the balloon film. Absorptivity gives the fraction of incoming light that is actually absorbed (and thus transformed into heat) by a surface. When its value is 0, this means that a surface does not absorb any incoming light, while if it is 1 the surface absorbs all the incoming light (and would be seen as completely dark). Emissivity is a bit more involved, as it is the ratio of the energy emitted by a body at a given temperature T to the energy emitted by a blackbody at the same temperature. A perfect blackbody has an emissivity of 1, while a body that does not radiate any energy (impossible from first principles) would have an emissivity of 0. Typically, absorptivity is relevant in the visible (because of the solar illumination), while emissivity is important in the infrared (because usual temperatures are between 200 and 300 K).

The material used by NASA for the SPB is the Linear Low Density Polyethylene (LLDPE) due to its density and mechanic and chemical properties such as elasticity, resistance to toxic gases, insulation and permeability. Its absorptivity is about 0.016 and its emissivity is 0.05.

Moreover, the planetary energy flux absorption depends on the absorptivity of the infrared radiation of the material but, as the First Kirchhoff Theorem states, this infrared absorptivity is the same as the infrared emissivity.

It must be also mentioned that the product of the albedo and the solar radiation flux corresponds to the solar radiation reflected on the planet's surface that reaches the aerobot surface.

Most calculations are done when the sun illuminates the aerobot (daytime), but this period of time is only part of the total day cycle, so the temperature at night must also be taken into account. Night temperature is determined by the Thermal Balance Equation in the same way as the diurnal temperature, but with no inputs from solar radiation (direct nor reflected).

Another parameter that changes is obviously the external temperature. The difference of the temperature of the environment at daytime and night depends on the planet atmosphere and the float altitude. For example, in the case of the Earth, the differential temperature at the lower stratosphere, where most weather balloons fly, is only of 1 to 3 K.

As was stated before, absorptivity and emissivity depend on the material, and so they do not change during the day/night cycle.

### 1.3.3. Differential pressure

Now is when it comes into play the most characteristic feature of the Super Pressure Balloon, the selected balloon system. As it has been explained before, in the SPB there is always a positive pressure differential between the interior of the balloon and the atmosphere, and so this initial condition is going to determine most of the system's parameters.

It must be remembered that this differential pressure must be enough to keep the aerobot at the same float altitude with the same volume, so there would be a minimum value for this pressure difference. On the other hand, the larger the differential pressure is, the higher the tensile stress of the balloon film is, and this tensile stress must be minimized in order to avoid possible breaks or other problems in the film. These two conditions mean that the optimal value of the differential pressure is the minimum needed to withstand the temperature variations between the daytime and night without modifying the float altitude and volume of the balloon.

The computation of this pressure differential is done by considering it as zero at night (as internal pressure at night is the minimum one). Following this, the gas density is calculated thanks to the Ideal Gas Law **(1.1)**. Then, the internal pressure at daytime can be determined using the same equation but now with the daytime temperature. Finally, the daytime differential pressure is the variance between this last internal pressure and the atmospheric pressure.

It is necessary to check that the resulting tensile stress is not larger than the maximum tensile stress that can be supported by the material of the aerobot film. The computation of the tensile stress is made using the Young-Laplace equation, which depends on the radius, so it is going to be explained in detail later (see equation **(1.9)**).

### 1.3.4. Gas pressure and density during ascension

After computing the differential pressure at daytime, this value is constant during the ascent in order to generate the lifting force.

Knowing this, it is possible to determine the internal pressure of the balloon at every altitude by only adding the differential pressure to the external pressure. Moreover, having the internal pressure for each altitude, the gas density can be computed by employing the Ideal Gas Law with this pressure and the internal gas temperature calculated before.

**Fig. 1.6** NASA SPB before launch

### 1.3.5. Maximum radius

To determine the radius of the aerobot at float altitude it is necessary to impose the equilibrium condition, which implies equalling the buoyant and the gravitational force. The buoyant force is computed using the Archimedes' Principle, which states that the lifting force exerted on a body in a fluid (atmospheric gas in our case) is the same as the weight of the fluid that the body displaces.

$$\rho_{out} \cdot V_b \cdot g = \rho_{av} \cdot V_b \cdot g = \left(m_{gas} + m_{cover} + m_{pl}\right) \cdot g \qquad \textbf{(1.5)}$$

$$\rho_{out} = \frac{m_{gas}+m_{cover}+m_{pl}}{V_b} \qquad \textbf{(1.6)}$$

$$\rho_{out} = \rho_{gas} + \frac{\rho_{cover} \cdot 4 \cdot \pi \cdot R^2 \cdot th + m_{pl}}{\frac{4}{3} \cdot \pi \cdot R^3} \qquad \textbf{(1.7)}$$

$$\frac{4}{3} \cdot \pi \cdot \left(\rho_{out} - \rho_{gas}\right) \cdot R^3 - \rho_{cover} \cdot th \cdot 4 \cdot \pi \cdot R^2 - m_{pl} = 0 \qquad \textbf{(1.8)}$$

The $\rho_{out}$, $\rho_{av}$, $\rho_{gas}$ and $\rho_{cover}$ are the densities of the atmosphere, the total aerobot, the buoyant gas and the shell of the balloon respectively, $V_b$ is the volume of the balloon, $m_{gas}$, $m_{cover}$ and $m_{pl}$ are the masses of the buoyant gas, the cover of the balloon and the payload, $R$ is the radius and $th$ is the thickness of the film. All these parameters are defined by the float altitude conditions, except the thickness, which is a fabrication characteristic.

Given this expression it is possible to extract the radius in the equilibrium altitude, which is also its maximum value. There are solutions of this equation, but only one of them is a real number, so this value is the right one.

The thickness of the LLDPE film usually employed by most of the Super Pressure Balloons by NASA is 38.1 microns and the density of this material is 915 kg/m$^3$.

### 1.3.6. Masses and tensile strength

At this point, the value of the maximum radius opens up many doors of essential data about the aerobot. Firstly it is easy to determine the volume of the balloon, considered as a sphere. Then, given also the lifting gas density, the mass of buoyant gas can be determined by multiplying its density and the volume.

Moreover, the surface of a sphere is $4 \cdot \pi \cdot R^2$, so this provides the area of the balloon film, which multiplied by its thickness corresponds to its volume. Finally, the only mass that remains to be determined is the cover mass, and it can be computed by multiplying its volume and density.

Apart from the masses, now the maximum tensile stress can be checked as it has been explained earlier. Surface tension is given by the Young-Laplace equation for a sphere,

$$\sigma = \frac{\Delta P \cdot R}{2} \tag{1.9}$$

where $\sigma$ is the surface tension, $\Delta P$ is the pressure differential between the gas and the environment and $R$ is the radius of the balloon. The maximum surface tension would be extracted by also using the maximum radius and differential pressure.

Then, this maximum surface tension determines the maximum tension along the circumference of the balloon shell $T_c$. This value allows measuring the tensile strength exerted on the circumferential section of the aerobot film $TS$.

$$T_c = 2 \cdot \pi \cdot R \cdot \sigma \tag{1.10}$$

$$TS = \frac{T_c}{2 \cdot \pi \cdot R \cdot th} \quad \textbf{(1.11)}$$

Now, the value of TS using the maximum radius must be compared with the Ultimate Tensile Strength (UTS) of the material, which defines the maximum force exerted to it before breaking. This TS must not exceed the UTS of the material. The UTS of the LLDPE is about 30 MPa.

### 1.3.7. Radius and vertical speed during ascension

Super Pressure Balloons are filled with all the mass of buoyant gas before launch, and so this mass is constant all along the ascension.

This means that, in order to compute the volume of the aerobot at every altitude, the only variable parameter is the gas density, which has been calculated previously. From this volume, it is possible to determine also the radius at every altitude by the formula of the volume of the sphere.

Furthermore, as now all the masses are known, the average density of the entire aerobot can be measured. Thanks to this, the forces of buoyancy and weight can be now calculated and, taking into account that during the ascension it appears a drag, the vertical speed is computed by:

$$\rho_{av} = \frac{m_{gas} + m_{cover} + m_{pl}}{V_b} \quad \textbf{(1.12)}$$

$$\text{Buoyancy} = \text{Weight} + \text{Drag}$$

$$\rho_{out} \cdot V_b \cdot g = \rho_{av} \cdot V_b \cdot g + \frac{1}{2} \cdot \rho_{out} \cdot v^2 \cdot c_d \cdot A_{cs} \quad \textbf{(1.13)}$$

$$v = \sqrt{\frac{2 \cdot V_b \cdot g \cdot (\rho_{out} - \rho_{av})}{\rho_{out} \cdot c_d \cdot A_{cs}}} \quad \textbf{(1.14)}$$

Here the new parameters are the drag coefficient $c_d$, which is considered 0.5 for a sphere on Earth, and $v$ is the vertical velocity of the aerobot during its rising. So, in order to compute the velocity at every altitude, the parameters of gravity, atmospheric density and radius must change at each height.

Finally, having this vector of the vertical velocities, it is possible to measure the time that the aerobot spends to reach its equilibrium altitude.

## 1.3.8. Diffusion, leakage and endurance

As is discussed in the “Super Pressure Balloon” section, the endurance of the aerobot is not limited by the release of ballast or the exhaust of the lifting gas. Nevertheless, there are two factors that determine the lifetime of the system: gas diffusion and leakage.

Diffusion is a process that consists in the motion of the molecules of the buoyant gas through the film of the balloon. The diffusion is directly proportional to the permeability ratio, which depends on the gas, its temperature and the material of the film. This implies that the value of the diffusion is different at daytime and at night, so these two values must exchange every half of the rotation period of the planet.

Unfortunately, there is not an analytic expression for the permeability, so its values must be extracted from documents or experiments of reference institutions like NASA, determined from many tests (see [4, 5]). Then, the computation expression of the diffusion is:

$$\mathrm{Diff} = \frac{\delta \cdot S_{cover} \cdot \Delta P}{th} \tag{1.15}$$

where $\mathrm{Diff}$ is the diffusion rate in $m^3/h$ and $\delta$ is the permeability of the material (which is experimentally determined). This diffusion rate determines the volume loss, and, using the density of the buoyant gas, it can be turned into a mass loss rate.

This phenomenon depends on the pressure differential, so it is also called mechanical diffusion. There is also another type of diffusion, which depends on the difference of composition between the inner and the outer gases, and it is called partial diffusion.

In the case of a SPB, the pressure difference plays a crucial role, so the effects of the mechanical diffusion are significantly higher than the penetration of the gases through the film due to partial diffusion effects. This implies that partial diffusion will not be negligible in this mission but it will be taken into consideration only qualitatively as it is a second-order effect.

Hence, the parameter that will determine the endurance of the balloon in the calculations is the pressure differential. From the diffusion rate it is known how much gas is lost during a given period of time, and so, in order to compute the lifetime of the system, the internal pressure will be computed every hour or day until the difference between this pressure and the outer one is negative (which is an unphysical assumption that would result from mass loss and will mark the end of the validity of the assumptions used for determining the characteristics of the balloon). When this difference is negative, the balloon will obviously collapse and the flight will terminate due to the impact of the system with the surface.

The minimum differential pressure at day is calculated considering that the pressure difference at night is 0, so this would cause a null endurance. In order to avoid this, a finite value of a pressure difference at night will be given, which means there will be a diffusion rate at day and another one at night. Given this, the balloon flies until the differential pressure at day or at night becomes negative. The pressure differential at night has to be an optimal value to maximize the lifetime of the aerobot without surpassing the maximum UTS of the material during the daytime.

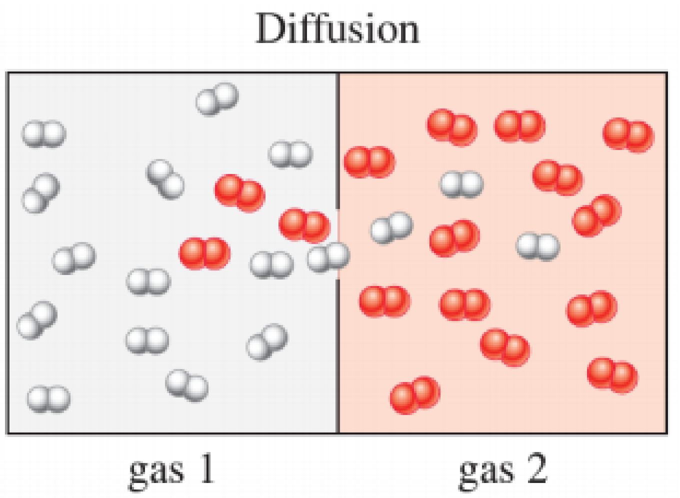



**Fig. 1.7** Mechanical diffusion between two gases

Leakage is the movement of the inner gas to the outside of the envelope due to manufacturing defects of the material. This parameter has a very indefinite value because it depends on the manufacturer and the atmospheric conditions, which may damage the film and make these holes bigger. It also varies along the envelope, as well as with time.

The most typical defects of a LLDPE film are called pinholes, holes of 0.1 mm of diameter. Fortunately, LLDPE is a material that has fewer pinholes than other balloon materials like Mylar. Leakage is a considerable factor for the endurance of the balloon, so this lifetime will be calculated with the values of the mechanical diffusion and with different values of a leakage rate. The values of the leakage rate through a pinhole at different temperatures are experimentally known (see [5]), so a close approximation can be estimated.

# CHAPTER 2. MARS APPLICATION

## 2.1. Planet study

The goal of this study is to design a balloon tailored to the Martian atmosphere. So, it seems appropriate to have a short analysis of the properties of Mars.

### 2.1.1. Atmosphere and surface

As is well known, Mars is a planet which differs from Earth in almost all the most significant characteristics of their atmospheres. The study of Mars for this mission will mostly englobe the physical properties and composition of its atmosphere, but many other factors such as its topography or its climate will be also taken into account in order to the future design of the aerobot.

This study focuses on the analysis of the characteristics of Mars compared to the corresponding values for Earth, so it is easier to have an overview of the differences between Mars and our environment.

Table 2.1 below lists some important atmospheric properties at the reference surface of the two planets to allow the beginning of the analysis of the Martian environment (see [6]).

**Table 2.1.** Earth and Mars atmospheric features at reference surface (sea level for the Earth, the datum –its equivalent– for Mars)

| DATA | EARTH | MARS |
|---|---|---|
| Air density ($kg/m^3$) | 1.225 | 0.014 |
| Pressure (Pa) | 101325 | 610.5 |
| Gravity acceleration ($m/s^2$) | 9.807 | 3.756 |
| Temperature at day (K) | 288.15 | 228.5 |
| Average diurnal temperature differential (K) | 15 | 30 |
| Air constant ($m^2/K \cdot s^2$) | 287.053 | 191.181 |

Then, it must also be mentioned that the Martian atmosphere is composed of a 95,97% of carbon dioxide, a 1,93% of argon, a 1,89% of nitrogen, a 0,146% of oxygen and a 0,0557% of carbon monoxide. These gases make Mars an obvious uninhabitable planet for human without artificial aids, so nowadays its exploration is limited to unmanned technology like landers and rovers (as well as future aerobots).

Obviously, this density difference directly affects the buoyancy force experienced by the aerobot. Now, in order to take the balloon to a given altitude, it is needed a lower density, so the size must be notably bigger. Furthermore, increasing the volume of the balloon increases also its weight, so the use of a light material as the LLDPE is mandatory. The fact that Martian's gravity is just 1/3 of Earth's helps the balloon to ascend.

The low thickness of the Martian atmosphere and its low atmospheric pressure explain the great diurnal temperature differential, which can achieve values of up to 100 K or more. The low air density increases the effects of solar radiation because there is not so much thermal protection as in the Earth, and this concomitantly reduces the greenhouse effect and the thermal inertia of the atmosphere. As a consequence, the current season also affects significantly in the temperature, especially when considering the large eccentricity of the orbit of Mars. These extreme changes add a difficulty at designing the aerobot, which must resist these thermal variations.

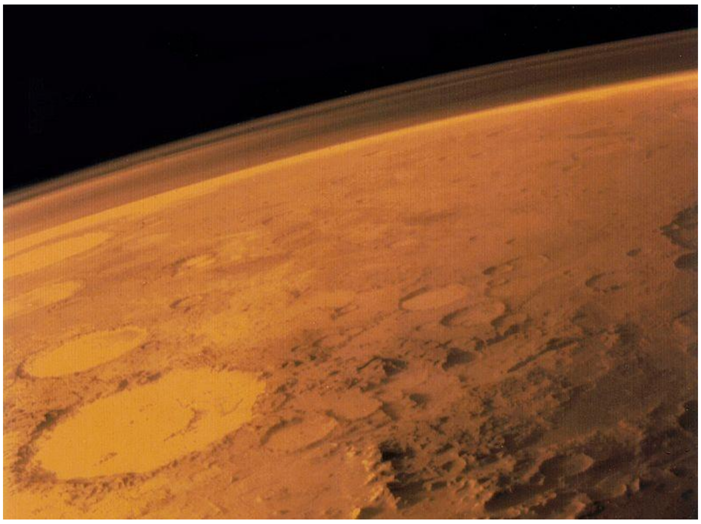


**Fig. 2.1** Mars' thin atmosphere

Nevertheless, not all the changes are detrimental. The mass and size of Mars are quite smaller than Earth's, and so the gravitational force is smaller too, as commented before. This reduction of the gravity acceleration is a benefit which implies that the required lifting force per unit mass can be diminished. This advantage slightly counteracts the required increase of the aerobot volume caused by the low atmospheric density.

Focusing on the surface, its most characteristic feature is the peculiar dichotomy of the Martian topography. As it is shown in Fig. 2.2, the geography of the two hemispheres differs drastically.

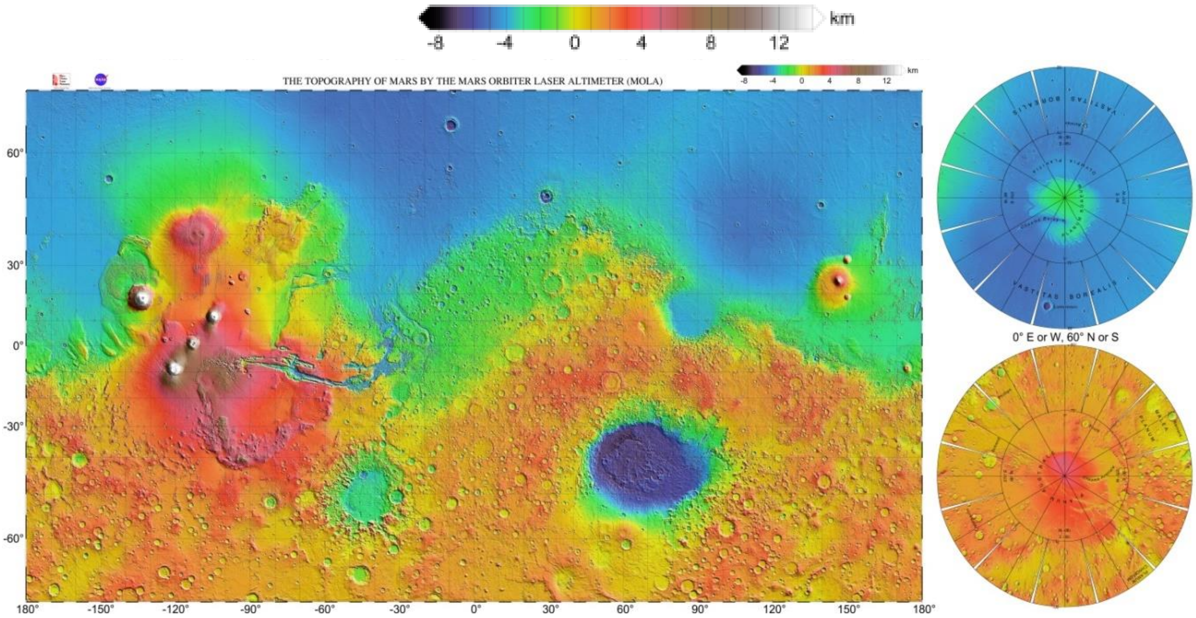



**Fig. 2.2** Topographic map of Mars based on the Mars Global Surveyor laser altimeter.

The northern hemisphere is characterised by lower large plains caused by lava flows of ancient volcanoes (it probably was also the bottom of an ocean billions of years ago) and the southern one has sharp mountains and valleys accompanied by a huge number of meteorite craters. These violent altitude variations of the terrain are not favourable to a safe flight of the balloon, so the track must be accurately determined. The flat extensions of the north are ideal for the landing and deployment of the balloon system.

Returning to the atmosphere, another factor that has to be considered is the wind generated by the circulation due to pressure change waves. This wind can achieve high velocities as is shown below.

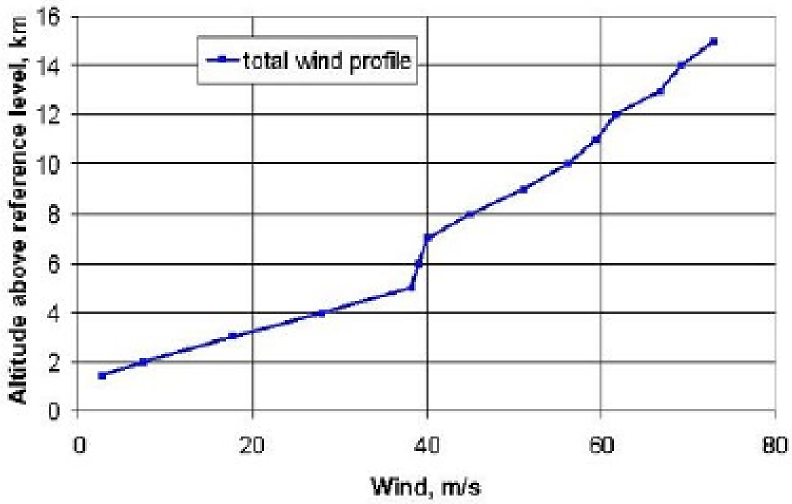



**Fig. 2.3** Atmospheric wind profile at latitude -50º from Mars-GRAM 2001

Although there are high wind velocities, it must be recalled that the air density of Mars is almost 100 times lower than in the Earth. This means that these speeds cannot be directly compared to wind speeds of the terrestrial atmosphere. In order to calculate the equivalent wind velocity on Earth's surface, it is necessary to study the dynamic pressure, which is the pressure generated by wind, and is given by the following expression:

$$P = \frac{1}{2} \cdot \rho \cdot v^2 \qquad \textbf{(2.1)}$$

Here $P$ is the dynamic pressure, $\rho$ is the air density and $v$ is the wind speed. The dynamic pressure of a wind in Mars is computed and then, using this dynamic pressure, we can compute the equivalent wind speed on Earth using the corresponding air density. Then, as the ratio of densities is about 100, the velocity on Earth will be a factor of 10 lower than in Mars to generate the same dynamic pressure.

Hence, wind effects are not as dangerous as they could seem given the low atmospheric density and the balloon track would not be so affected as if it flew on Earth. Nevertheless, wind can produce dust storms that can be active for weeks or even months and can even cover the entire planet, as happened in 2001. These whirlwinds and storms can achieve heights of a few kilometres.

Mars' surface is mostly a desert composed by tiny solid particles called Martian soil. As it has just been explained, wind speeds in Mars are less powerful than they seem, so apparently these velocities would have to be large in order to lift this dust from the surface, but this is not completely true. As Mars' climate is dry and cold, the soil is not aggregated by moist and dust is not only easily lifted to high altitudes but it can also remain in the atmosphere for long periods due to its small size (4 microns in average). This means that these particles can be found at high altitudes even beyond any possible balloon float altitude, up to 50 km over the datum. While their actual velocity does not make these particles very dangerous, their force can be enough to create tiny holes in the shell of the balloon.

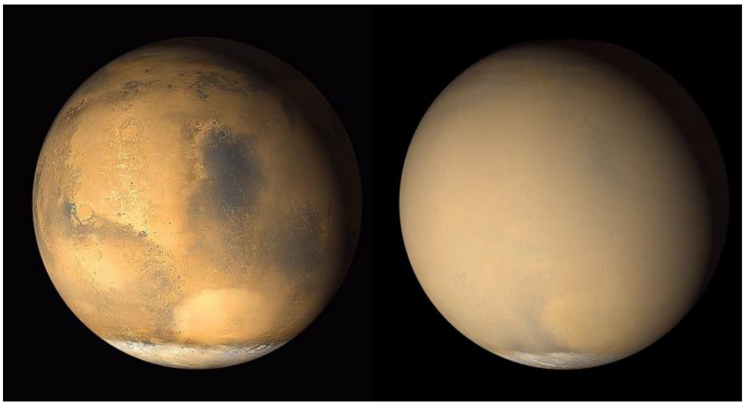


**Fig. 2.4** The global dust storm in 2001

### 2.1.2. Atmosphere model

Table 2.1. indicates the values of many important features of the atmosphere of Mars at its datum. But, in order to compute the properties of the balloon for every altitude, an atmosphere model must be used.

There are many Mars atmosphere models such as the Mars-GRAM or the Mars Atmosphere Model made by the Mars Global Surveyor in April 1996. The first one is too complex and tangled in order to compute the expressions required in a quick and practical way by just changing the different parameters. The second one is also a good reference but it only provides temperature and pressure data from 0 to 7 km (it gives these data beyond 7 km just during daytime).

For our work, an optimal atmosphere model is one that provides information about dayside and night, which is really important due to the significant diurnal temperature differential, easy to deal with in order to compute and extract the needed data, and with a reliable source behind it. Given these three conditions, the optimal model for our purposes is the **Viking-Pathfinder Atmosphere Model**.

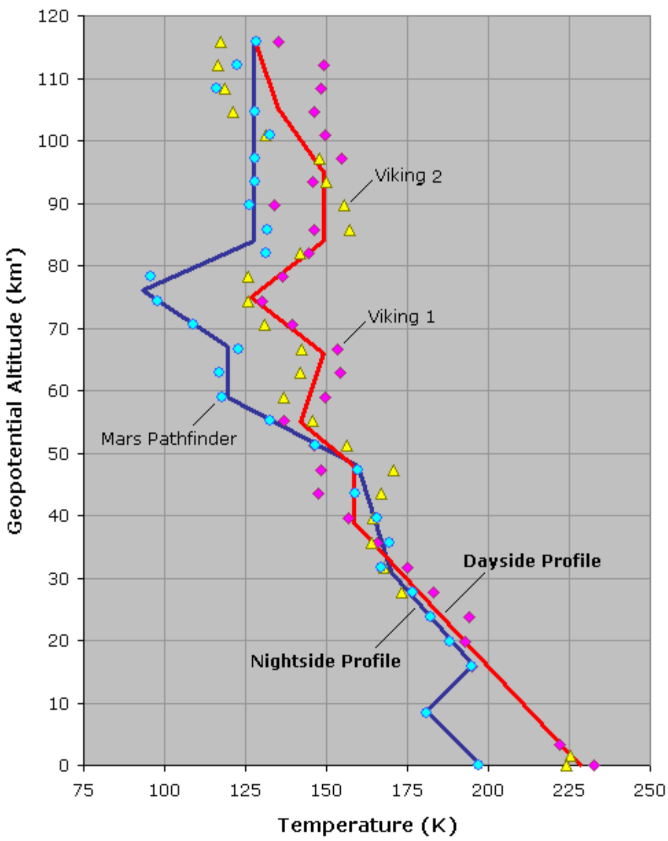



**Fig. 2.5** The Viking-Pathfinder Atmosphere Model

As its name conveys, the Viking-Pathfinder Atmosphere model is based on the measures by two sources: the Viking program spacecrafts and the Mars Pathfinder.

The dayside temperature and pressure profile data were taken by the spacecrafts Viking 1 and 2 in 1976 at the coordinates of (22º, -50º) and (48º, 135º) respectively.

The nightside temperature and pressure profile data were taken by the Mars Pathfinder spacecraft in 1997 at the coordinates of (19º, -33º), close to the landing site of the Viking 1. They all landed during the summer season, which favours a better solar irradiance needed to breed the solar cells of the spacecrafts to produce electricity, but reduces the applicability of the atmospheric model for all seasons.

The landing coordinates indicate that the landing sites correspond to the flat terrains of the northern hemisphere that have been shown previously in the topography section. As shown in Fig. 2.2, these regions are located approximately 3600 m below the zero level of Mars datum, the Martian equivalent to our sea level. This depth is the value that will be used for the aerobot's landing place and deployment, due to the optimal conditions of this terrain.

As it is shown in the temperature profile of Fig. 2.5, at low altitudes there is a large diurnal temperature differential, of approximately 30 K. From 8 km and above, the temperature at night rises with altitude until it reaches values close to the dayside conditions.

The optimal altitude range for the aerobot of this mission will be from 6 km to 12 km approximately. The lower boundary is limited by the irregular and sharp terrain of most of the Martian surface. A float altitude of 6 km allows the system to fly over almost all Mars without colliding with mountains or any obstacle. A too low altitude would also imply coming into conflict with the trajectory of a dust storm or whirlwind, or getting too much in contact with dust particles which could damage the balloon shell or the experimental payload.

The upper boundary is limited by two factors too. Beyond 12 km the wind speeds produce a horizontal force that really affects the aerobot track and also to its equilibrium safety. As it is shown in Fig. 2.3, at 12 km this speed is of 63 m/s approximately, which means an equivalent velocity on Earth's surface of 4.1 m/s (15 km/h). The other cause is that the further the aerobot is from surface, the worse the experiments resolution is, so a high altitude may be useless for the exploration. On the other hand, in a low equilibrium altitude the resolution is better, but the field of view is too limited, so the optimal float altitude must be at an intermediate level.

**Fig. 2.6** A dusty whirlwind from a high-resolution camera.

After determining the interval of the optimal float altitudes, let's describe the Viking-Pathfinder Atmosphere Model. The atmospheric temperature measure is determined by a constant gradient law (but its value changes in different layers).

The expression to compute the atmospheric pressure is given by:

$$T(h) = T_o + \Delta T \cdot h \qquad \textbf{(2.2)}$$

$$P(h) = P_o \cdot \left(\frac{T_o}{T(h)}\right)^{\left(\frac{g_o}{R_a \cdot \Delta T}\right)} \qquad \textbf{(2.3)}$$

where *P(h)* and *T(h)* are the atmospheric pressure and temperature at every altitude, $P_o$ and $T_o$ are the atmospheric pressure and temperature at the base of the layer, $g_o$ is the surface gravity, $R_a$ is the Martian air constant and $\Delta T$ is the temperature gradient in K/m, which can be positive or negative.

So, knowing the general expressions of atmospheric temperature and pressure and the surface data given by the previous table 2.1., the only parameter that is given by the atmosphere model are the temperature gradients. Knowing also the optimal range of float altitudes, from 6 to 12 km, it can be seen that there is only one layer for the diurnal profile of temperatures and two layers for the nightside profile, having their separating boundary at 8500 m.

As has been explained before, the aerobot deployment will take place close to the landing sites of the Viking and Mars Pathfinder spacecrafts, so its initial altitude will be 3600 m below the datum according to their landing coordinates. As demonstrated by the measurements of the Viking 1 spacecraft (see [7]), the trend of the atmospheric temperature below the zero level of the datum is very similar as in this zero level, so the temperature gradient will be considered the same as in the first layer of the atmospheric model. It can also be seen that the pressure at the landing site is very similar to the one in the zero level of the datum.

The table below shows the values of the temperature gradients in K/m of both profiles of these stages.

**Table 2.2.** Temperature gradient of the different stages.

<table>
<tr><th>STAGES</th><th>Dayside profile</th><th>Nightside profile</th></tr>
<tr><td>From -3.6 to 8.5 km</td><td rowspan="2">-0.0018 K/m</td><td>-0.002 K/m</td></tr>
<tr><td>From 8.5 to 12 km</td><td>0.0019 K/m</td></tr>
</table>

Finally, the Martian air density is computed by employing the Ideal Gas Law using the previous atmospheric temperatures and pressures of each altitude.

Now, after computing the atmospheric temperature, pressure, air density and gravity, the main atmosphere model of Mars for this mission is completed.

In order to fully complete the necessary data of the Martian atmosphere, the following table shows the values of some significant information about Mars (see [8, 9]):

**Table 2.3.** Important data of Mars for future computations

| Planet radius | Albedo | Solar irradiance | Planetary irradiance | Stefan-Boltzmann constant |
|---|---|---|---|---|
| 3389.5 km | 0.25 | 586.2 W/m$^2$ | 110 W/m$^2$ | $5.67 \cdot 10^{-8}$ W/m$^2 \cdot$K$^4$ |

## 2.2. Aerobot design background

Since the decade of the 70s, Mars' exploration has been one of the main objectives of space science. The goal of studying the most similar planet to Earth on the Solar System and the desire of discovering indigenous life forms, have always been strong motivations to encourage scientists.

Unfortunately for this project, these spacecrafts have always been, in first-time chronologically order, flybys, orbiters, landers and rovers. An aerobot or other balloon systems has been tested on Earth with similar conditions to Mars ones, but even the projects that seemed more feasible were cancelled. Nevertheless, the research continues and many experiments and designs are still being tested nowadays and, at this rate, more of them will be developed until a so longed future mission is approved.

Below, there is a list of the most relevant designs and tests of some balloon systems focused on Mars exploration.

### 2.2.1. Mars-94

The first notable project was an aerobot design that began at the mid-1980s by French and Soviet scientists, and which eventually became a global mission which included more than 20 participant countries as the UK or the USA (see [10]).

Its launch was set to be in 1994, as the name of the mission indicates, but it was cancelled in 1992 due to the Soviet Union dissolution and the resulting financial crisis of the Russian Space Agency.

The balloon envelope conception was made by the French CNES and the Soviets hold the task of defining the gondola and the delivery of the aerobot to Mars.

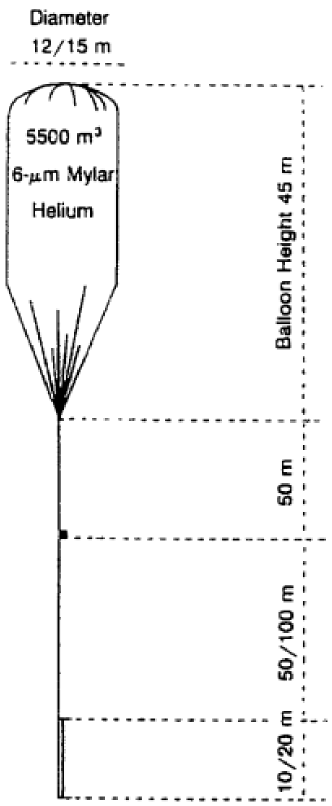



**Fig. 2.7** The Mars-94 balloon system

The aerobot was a super pressurized balloon that, because of the limited film technology of these years, only could fly during the day. The balloon envelope was about 5500 $m^3$ when fully inflated, it had a cylindrical shape in order to support tension forces with a thin film and the material was a transparent Mylar film of 6 microns that minimized radiation cooling and heating.

The top of the balloon would be filled with helium and the bottom of it had air from the Martian atmosphere. During the day, the helium and atmospheric air are heated and make the aerobot rise from 2 to 4 km above ground. Its track is determined by the Martian winds. A high-resolution camera would take pictures of the Martian surface, which would be transmitted later to the Soviet and American orbiters, and finally to Earth.

Then, at night, the gases cool down and the balloon descends. The balloon would rest on the surface and the gondola would not touch the ground thanks to the guide rope, shown in Fig. 2.7, suspended from the gondola that relieves the negative buoyancy of the system(by the simple fact that part of its weight is not acting on the balloon while it lays on the ground). This guide rope would have some instruments attached to it, which would also make some measures on ground.

The mission would last about 10 days until the gas would be leaked through the film. At that time, it was calculated that the aerobot would have travelled approximately 1500 km.

### 2.2.2. MAP and MABS 2001

After the Soviet Union collapsed, the Mars-94 was cancelled and many years passed with only a few unsuccessful tries of the French, until in 1994 the NASA Discovery Program proposed the MAP (Mars Aerial Platform) project (see [11]).

It consisted of a system formed by two superpressure balloons of biaxial nylon 6 and 12 microns thick, and a small gondola of 7kg. The aerobot was thought to fly at constant altitude in nominal atmospheric conditions. It included many innovations but it was not completed due to the lack of technology at the balloon envelope design.

The MAP study and the failed French designs were the base of a still more ambitious design in late 1995 and 1996 called MABS 2001 (Mars 2001 Aerobot/Balloon System), which was estimated to be launched in 2001 (see [11]). The Jet Propulsion Laboratory (JPL) initiated this project, and then many other organizations such as the NASA Goddard Space Flight Centre or the CNES joined the research.

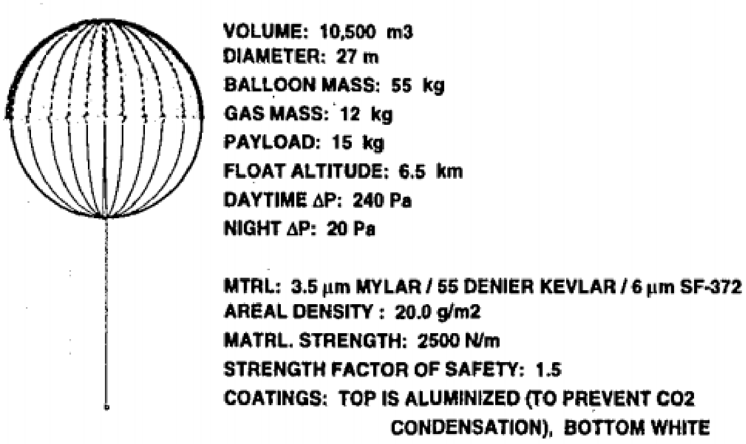



**Fig. 2.8** The MABS 2001 balloon system

As it is shown in this Fig. 2.8, the MABS 2001 balloon system idea is similar to the superpressure balloons launched by NASA: a spherical superpressure balloon with a gondola attached by means of a long rope.

The most relevant improvement was the variety of the materials used for the balloon envelope film (Mylar, Kevlar and Polyethylene), which provided minor leakage and a better resistance to tension forces, mostly caused by the Polyethylene. It was also thought that the aluminization of the top of the balloon would prevent harmful effects of the condensation of the $CO_2$.

This composite film provided a greatly higher resistance to pinholes that cause a high leakage rate, so now the estimations of the endurance of the aerobot were more optimistic, reaching even a lifetime of 90 days. However, even if this composite material met these requirements, the technology of that time did not make possible to develop and optimize this film for full scale production.

### 2.2.3. Mars BGS

It was necessary to wait until 2006 to find another project that introduced many new aspects that made a real Mars aerobot closer to a real design. The Global Aerospace Corporation (GAC) was the organism backing a project which involved a Mars aerobot with a new system called BGS (Balloon Guidance System) (see [12]).

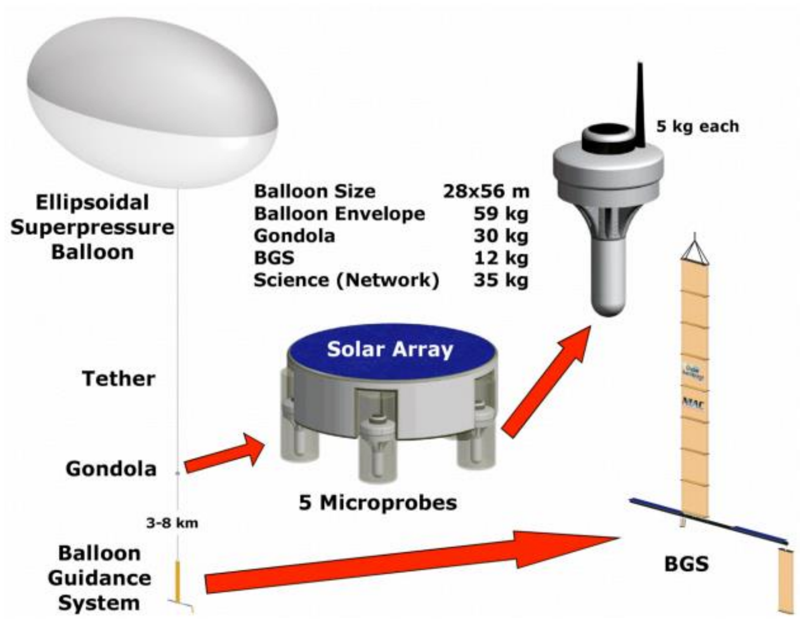



**Fig. 2.9** The guided Mars balloon platform of GAC

This concept returns to the “guide rope” idea of the Mars-94, but with a greatly improved system. This BGS is continuously in use because now the aerobot flies day and night and does not rest when there is no sunlight, but it requires a little power to work (1 W approx.).

The BGS has four main objectives:

- Avoiding the gondola from hitting the surface which can damage it.
- Being part of the scientific payload taking measures from the surface.
- Deploying some microprobes to the surface from the aerobot.
- Controlling the balloon direction and track thanks to a wing that generates a horizontal lift force.

This horizontal lift force depends on the size and shape of the wing, the float altitude (density of air), and the relative wind between the wind on the BGS and the wind on the balloon. The performances of the BGS were proved in tests on Earth.

The balloon envelope material is composed by thin film of Mylar of 1 micron, a PBO thread of 38 Denier and a thicker 3-micron film of Polyethylene. It has an ellipsoidal shape due to the drag forces are reduced if the long axis is in the direction of the balloon’s relative wind, but the area and the masses of the balloon system are increased a 10% (it might not be a good idea for Mars, whose atmosphere forces a huge balloon volume). The flight duration is now also really increased until a value of 700 days approximately.

### 2.2.4. MAPS

In 2012, the JPL introduced a new proposal for a Martian aerobot. The project was called MAPS (Mars Airborne Prospecting Spectrometers) and its main focus was to design a significantly more complex gondola that incorporated completely new technology for Mars exploration, most of it from the field of physical optics (see [13]).

Apart from the scientific payload, there was also a brand new concept for the most important part of the aerobot that concerns this project, the balloon system. The design is called a hybrid balloon, which is composed by a typical SPB with a propeller attached to it powered by an electric engine.

This engine is supplied of electric energy by solar cells, which are located just along the envelope surrounding it. This system of solar cells is called flexible solar skin, developed by CalTech, and consists on a large, flexible, thin (less than 100 microns) and highly efficient photovoltaic cells wall.

Due to the required cutting-edge technology, this design is expected to be a feasible mission between the years 2018 and 2024.

### 2.2.5 Montgolfiere

Finally, there have been several projects that considered using a Montgolfiere, also known as hot air balloon, to fly on Mars. The JPL with NASA are the most relevant organisms to have performed studies about this type of balloon system (see [14, 15]).

As previously explained, hot air is heavier than helium, but the conditions on the atmosphere of Mars make it a feasible option. Nevertheless, the altitude reached would not be as high as the float altitude of a SPB due to the low atmospheric temperature; hence, the risk of hitting the surface is higher.

The hot air of the balloon is heated by the sun, so the other disadvantage is that the aerobot would have to rest on surface at night, limiting its exploration capabilities.

Following these facts, it was concluded that a Montgolfiere on Mars would have two utilities:

- It can be used as soft-landing parachute in case of large and fragile payloads because they are more stable than ordinary parachutes, and the impact velocity could be reduced by a factor of 10 (and so the vertical impact energy would be reduced by a factor of 100). It is also a cheaper option than a retro-rocket landing system.

- It can be used as low-altitude aerobot with the mission of sampling any material from the Martian surface like ice or soil. A vent could help the balloon to control its altitude.

## 2.3. Aerobot basic design

We will now compute the main characteristics of a basic aerobot. The system is called a “basic aerobot” because it is composed of a simple SPB envelope with a payload mass which is not going to be explained in detail here.

To begin with, some parameters will be fixed and then, employing the formulas shown in the “Balloon Physics” section, the values of the characteristics and performances of the aerobot will be determined.

### 2.3.1. Preliminary considerations

The first step is determining the atmosphere model on which the measures will be based. As explained before, the Martian atmosphere model used in this project is the Viking-Pathfinder model. Its details have been described in the “Atmosphere model” section.

The material of the envelope is the one used in the Super Pressure Balloon of NASA, the Linear Low Density Polyethylene (LLDPE). LLDPE has a great resistance to the generation of pinholes, which extends its endurance, and provides high fracture toughness compared to the Mylar, the other most typical material in aerobots. Table 2.4 lists some characteristics of the LLDPE film, also taken from the NASA SPB program.

**Table 2.4.** LLDPE film characteristics

| | |
|---|---|
| Density | 926 kg/m$^3$ |
| Thickness | 38.1 μm |
| Ultimate tensile strength | 30 MPa |
| Absorptivity (see [16]) | 0.016 |
| Emissivity | 0.05 |

Moreover, the shape of the balloon will be considered spherical, so the radius is constant all along the envelope, and the computation of the balloon volume is the same as the one explained previously.

As was discussed in the “Types of buoyant gas” section, the chosen floating gas is helium which is also the buoyant gas used in the NASA SPB.

The floating altitude will be in the range from 6 to 12 km above the datum. It is a compromise between the need to avoid dust storms and possible obstacles at low altitudes, and a worse resolution and faster winds at high altitudes. The aerobot features are determined as a function of altitude. Furthermore, the data for a specific altitude will also be exposed and analysed. **The specific float altitude chosen is 8 km above the datum**, which is an altitude that ensures a good ground resolution while, at the same time, greatly reduces the possibility of colliding with volcanoes or the surface.

The landing site is located on the large plains of the northern hemisphere, close to the Viking landing coordinates. This implies that the elevation at this point is approximately 3600 m below the zero level of the datum, so the computation will cover from this negative elevation to 12 km above the datum. In the plots, the landing site height is the zero level of this mission, so the maximum altitude of the calculations will be 15600 m. Then, the optimal float altitude range will be comprised between 9600 m and 15600 m, and the specific float altitude will correspond to 11600 m.

Finally, the payload mass has also to be fixed. The low atmospheric density causes a really large balloon volume as compared to similar balloons in the Earth. As a consequence, the payload must have a small weight in order to minimize this volume increase. This mass will be fixed in 10 kg, including the scientific gondola (housing the payload and the bus) and the rope that connects this gondola to the balloon.

## 2.3.2. Computations and results

The beginning of the calculations is the atmosphere model; so, thanks to formulas **(2.2)** and **(2.3)**, the plots of the atmospheric temperature and pressure can be determined (see figures 2.10 and 2.11).

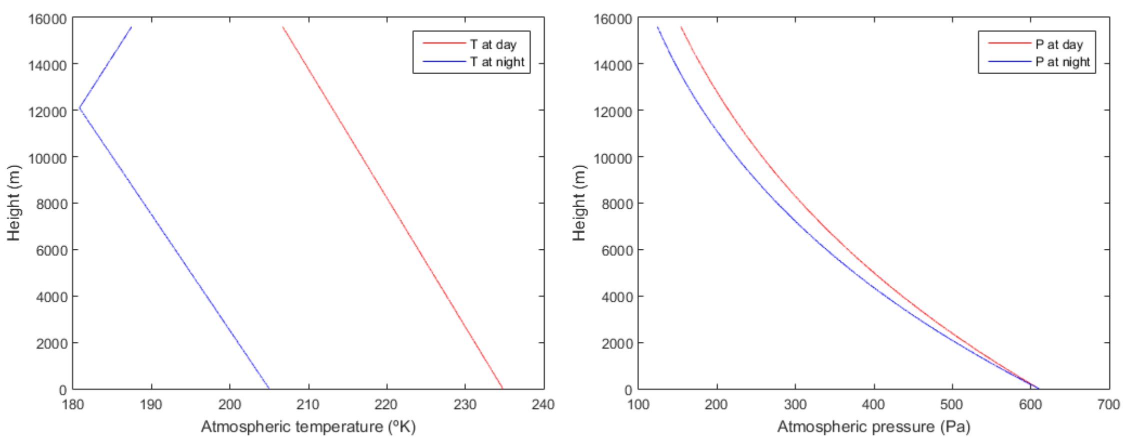



**Fig. 2.10 and 2.11** Atmospheric temperature and pressure vs height

The air density and the gravitational force can also be plotted using the formulas **(1.1)** and **(1.2)** and are shown in figures 2.12 and 2.13.

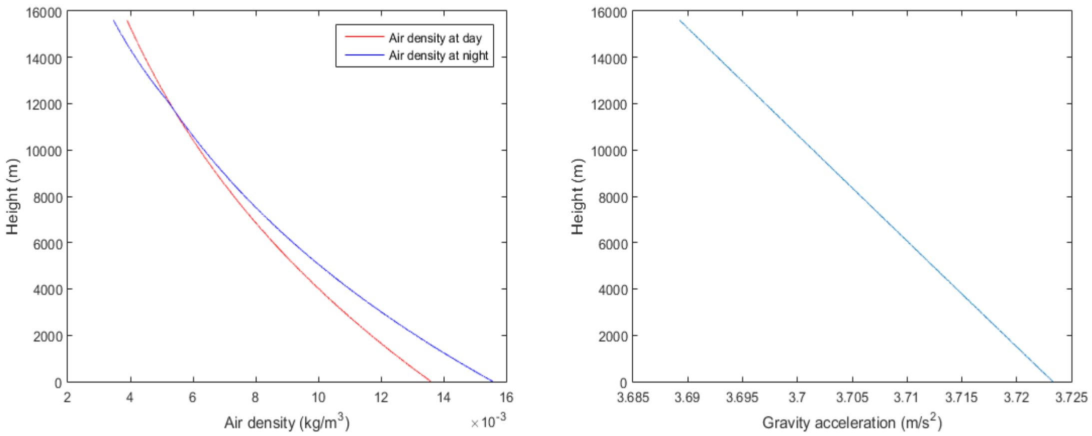



**Fig. 2.12 and 2.13** Atmospheric air density and gravity vs height

The atmospheric temperature corresponds to the atmospheric model in Fig. 2.5. Moreover, the pressure decreases considerably with altitude, the same as the air density. This shows that choosing one float altitude or another really affects the environment of the balloon and, directly, its characteristics are affected too. The gravitational force remains nearly constant, so it will have almost no influence at all.

Then, the values for the specific altitude of 8 km below the datum are given in table 2.5.:

**Table 2.5.** Atmospheric characteristics at specific altitude

| Atm. temperature (day/night) (K) | Atm. pressure (day/night) (Pa) | Air density (day/night) ($kg/m^3$) | Gravity ($m/s^2$) |
|---|---|---|---|
| 213.92 / 181.8 | 222.88 / 189.57 | 0.0055 / 0.0055 | 3.698 |

It stands out that the air density is just the same at day and night. This is a great advantage for the balloon system and is another reason why this specific altitude has been chosen. The benefit of this fact will be explained later when the radius of the balloon is computed.

Now, having the environmental values, it is time to start determining the different aerobot properties. Firstly, the buoyant gas temperature is measured thanks to the thermal balance equation **(1.4)**. Here, the data of tables 2.3 and 2.4 are used.

Having all the required values, the internal temperatures at day and night can be obtained. From now on (with the exception of the values of the ascension of the balloon), the characteristics of the aerobot are displayed in the optimal float altitude range because they correspond to the balloon system at equilibrium.

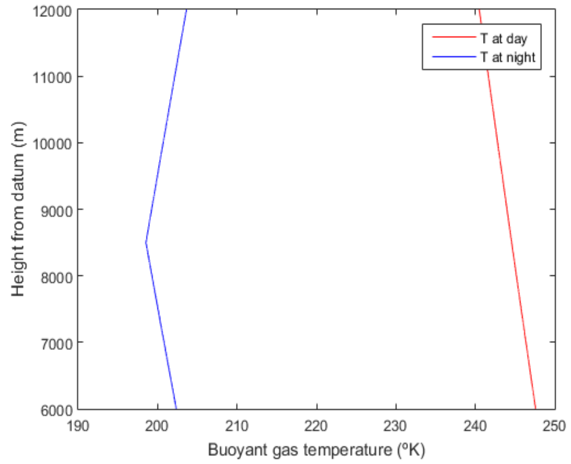



**Fig. 2.14** Buoyant gas temperature vs height

It is interesting to note that both internal temperatures at day and night are higher than the external corresponding atmospheric temperatures, but this increase is slightly larger for the diurnal temperature. This means that the temperature difference is even higher inside the aerobot, which makes also larger the required pressure difference in order to maintain the balloon floating at constant altitude.

**Table 2.6.** Buoyant gas temperatures at specific altitude

| Gas temperature at day (ºK) | Gas temperature at night (ºK) |
|---|---|
| 245.17 | 199.29 |

The following step is determining the pressure differential, which is the key to the rest of the computations. As it is demonstrated in the “Balloon physics” section, the pressure differential at night has to be almost null in order to minimize the diurnal pressure differential, but this would make the endurance almost null too. This means that the pressure differential at night must be an optimal value that maximizes the endurance without surpassing the maximum UTS because of a big diurnal pressure differential.

After some tests, it has been found that a reasonable value is about **70 Pa**. It will be shown later that this value corresponds to a big tensile strength that does not surpass the UTS of the LLDPE film. After this, using the corresponding formulas, the internal pressures, pressure differential between the internal and the external pressure at day, and helium density are the ones shown in figures 2.15 and 2.16.

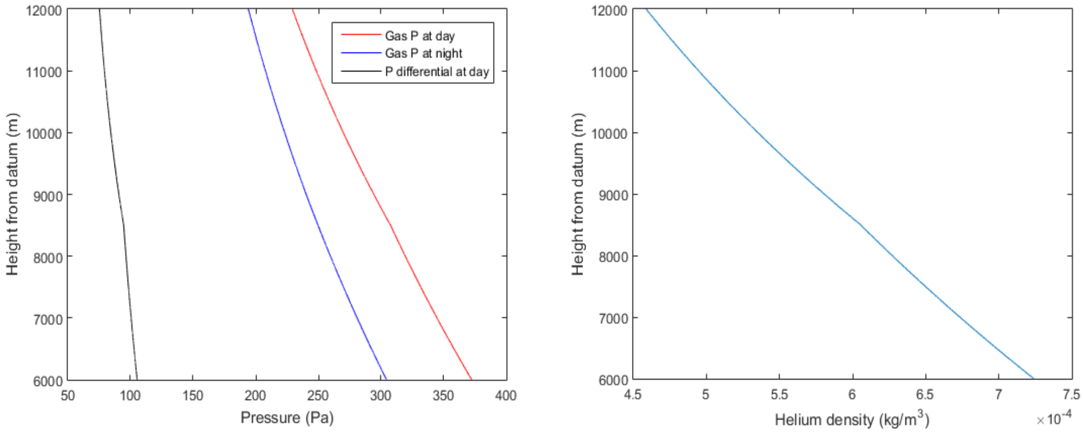



**Fig. 2.15 and 2.16** Gas pressure and pressure differential at day, and gas density vs height

As the floating altitude increases, the internal pressure decreases as well as the external one. Furthermore, the resultant diurnal differential pressure at day also decreases with height.

About the helium density, it clearly decreases with altitude. This does not also mean a decrease in the gas mass because there is no loss of buoyant gas, but is related to the increase in the volume of the balloon with altitude due to the decrease of the air density. The fact that it does not change during the day/night cycle is because the helium mass does not change (there are no vents in a SPB) and neither does its volume (as will be shown later).

**Table 2.7.** Buoyant gas pressures, diurnal differential pressure and density at specific altitude

| Internal pressure (day/night) (Pa) | Differential pressure at day (Pa) | Helium density ($kg/m^3$) |
|---|---|---|
| 319.33 / 259.57 | 96.45 | $6.27 \cdot 10^{-4}$ |

Here, the ascension parameters are calculated as a function of altitude while the aerobot is rising. This ascension is performed at daytime. Using the diurnal pressure differential that has just been calculated, it is possible to determine the internal pressure and the helium density. This pressure differential in a SPB is constant all along the climbing.

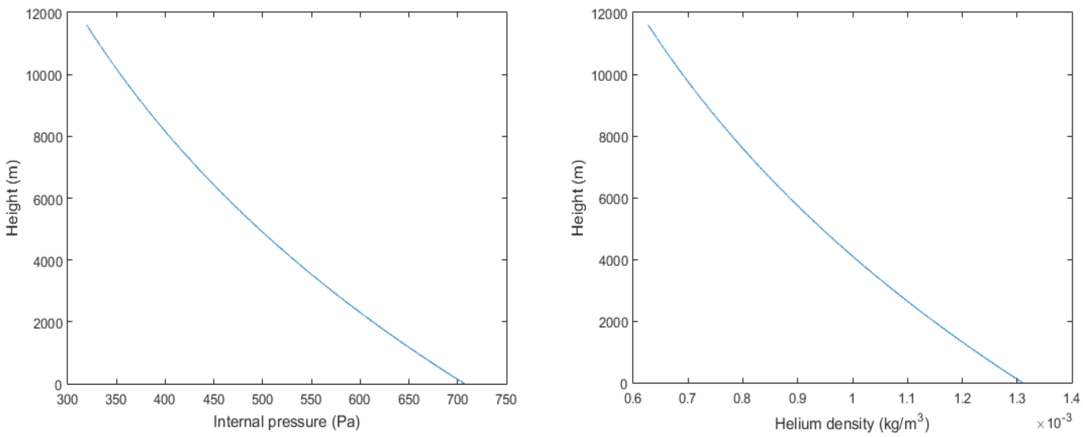


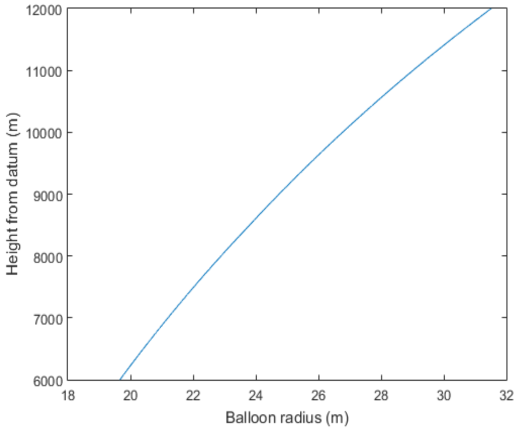

**Fig. 2.17 and 2.18** Internal pressure and helium density during ascension vs height

Figures 2.17 and 2.18 represent the ascension of the balloon, so the height is from the landing site until the specific float altitude.

Now we can determine the building aspects of the aerobot. We begin by computing the maximum radius of the balloon to calculate the balloon volume. From this volume, the masses of the envelope and helium can also be measured. Equation **(1.8)** shows that the only changing parameters in the computation of the radius are the air and helium densities.

The atmospheric density at a given altitude changes only because of the day/night cycle, but, as it has already been shown, air density does not vary at the chosen specific altitude, so the radius will also be constant at night. This is the great advantage of this floating altitude. The radius is neither affected by the internal changes of pressure and temperature thanks to the stiffness of the film generated by the pressure differential. This is why the helium density does neither change.

Following these statements, it can be said that the maximum radius of the balloon does not vary and the equilibrium altitude is constant along the day/night cycle for the specific float altitude. For other altitudes, the corresponding atmospheric air density at night must be identified in fig. 2.12, which can provide the resulting float altitude at night. For altitudes higher than the specific one, the balloon will descend at night, and for altitudes lower than the specific one, the aerobot will ascend at night.



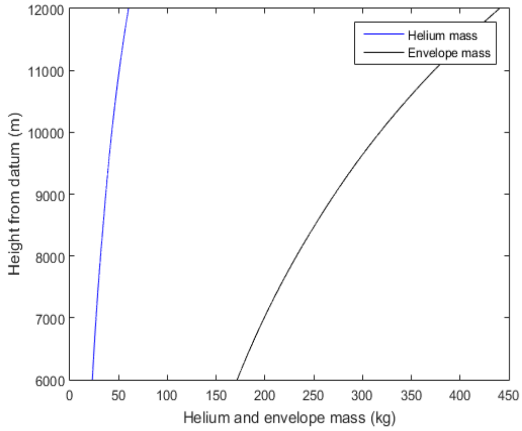




**Fig. 2.19 and 2.20** Balloon maximum radius and masses vs height

As buoyancy requires a high balloon volume, envelope and helium masses are correspondingly large. Furthermore, Martian low atmospheric density implies a huge volume for the 10 kg of payload compared to Earth, even for low altitudes.

In order to decrease this volume, the balloon fabric’s thickness could be reduced, but there are two disadvantages on changing it; the tensile strength is increased and the endurance is reduced (as it is shown in formulas **(1.11)** and **(1.15)**), so it is not a worthy option.

The helium mass does increase so much because, as it is displayed in fig. 2.18, the gas density decreases with altitude. This also shows that this increase is so considerable that a low altitude as the chosen specific altitude is better to reduce the total weight of the system.

**Table 2.8.** Maximum size and masses of the balloon

| Maximum radius (m) | Maximum volume ($m^3$) | Helium mass (kg) | Envelope mass (kg) |
|---|---|---|---|
| 22.89 | $5.02 \cdot 10^4$ | 31.5 | 232.32 |

Now, with the differential pressure and the size of the balloon, the tensile strength can be computed. The tensile strength must not surpass the UTS of the LLDPE, which is 30 MPa; otherwise, the balloon would burst.

Tensile strength is maximized to a close value to the UTS for each differential pressure, which depends on the selected specific float altitude. This means that it would be similar to these 30 MPa for every altitude, which implies that the other parameters calculated since now would change if the specific altitude is changed, so the following plot is for the conditions of this project.

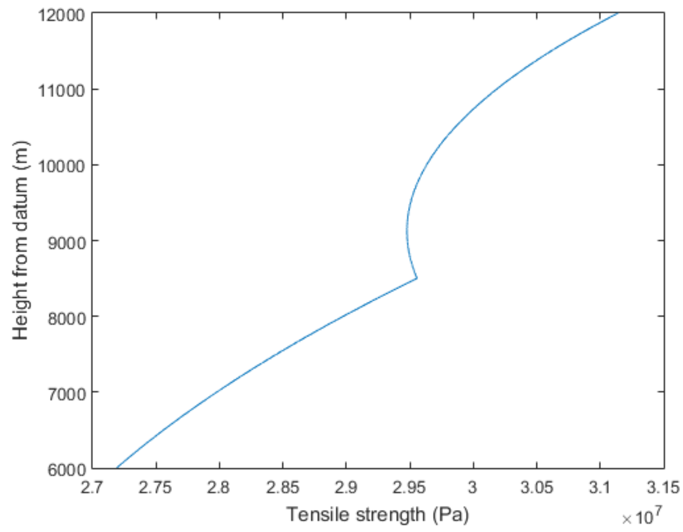



**Fig. 2.21** Tensile strength vs height

Figure 2.21 shows that, with the conditions of this project (specific float altitude, film thickness and pressure differential at night, which depends on the previous two), the balloon envelope would break above approximately 11 km from zero level of the datum.

The change in slope in the curve is caused by the change of the temperature gradient at 8500 m, which affects the pressure differential too. Although quantitatively it does not mean a great variation, it actually allows the aerobot to fly much higher.

The tensile strength at the chosen specific altitude is 28.97 MPa.

In order to compute all the ascension parameters, the radius and the velocity of the aerobot while it rises must be determined. The speed calculation requires a value for the drag coefficient. Knowing that the Reynolds number of the balloon in the Martian atmosphere goes from $10^4$ to $10^5$ (see [17]), then the drag coefficient of a sphere for these values is 0.5 (see [18]).

Considering this, the evolution of the radius of the balloon and its vertical speed along the ascension until reaching the specific float altitude is shown in figures 2.22 and 2.23. Again, the heights represented are the ones from the landing site to the equilibrium altitude.

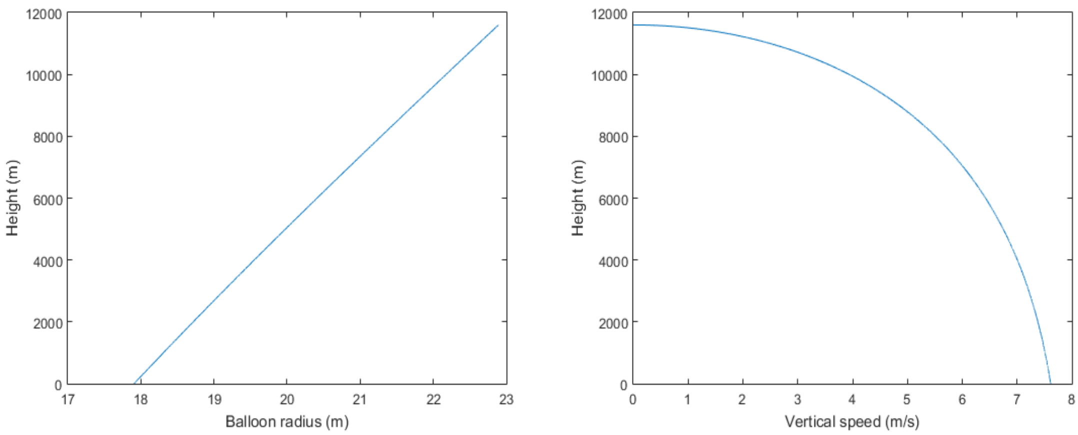



**Fig. 2.22 and 2.23** Balloon radius and vertical speed during ascension vs height

Fig. 2.22 shows that the balloon has to be inflated with a radius of almost 18 m to start rising. During the ascension, the helium expands until reaching the maximum radius at the equilibrium altitude. The gas mass does not change because the system is entirely filled on ground, but its density changes with altitude, as previously determined.

In fig. 2.23 it is shown that the balloon initially rises with a high vertical velocity, which is dramatically reduced when the balloon is close to the float altitude. From these speeds, it is possible to find the time that the aerobot needs to reach the float altitude.

The resulting time to reach the specific float altitude is a bit more than 43 minutes (2605 seconds), which is quite a short time.

Finally, the last step is to determine the lifetime of the system. This endurance is limited by the pressure differential, so when this becomes negative due to the gas diffusion and leakage, the aerobot collapses.

Gas temperatures at day and night allow extracting the permeability (see [4, 5]) of the balloon’s fabric. This procedure depends on the internal temperature but there is not a fixed expression for this permeability, so, unfortunately, cannot be plotted for different specific float altitudes.

Focusing on the specific equilibrium altitude selected for this project, the permeabilities and the diffusion rates at day and night are the ones below:

**Table 2.9.** Permeability and gas diffusion rate at day and night

| Permeability ($m^3 \cdot m/m^2 \cdot Pa \cdot h$) | | Diffusion rate (kg/h) | |
|---|---|---|---|
| Day | Night | Day | Night |
| $3.382 \cdot 10^{-14}$ | $1.35 \cdot 10^{-15}$ | $3.535 \cdot 10^{-7}$ | $1.411 \cdot 10^{-8}$ |

As the gas diffusion rate values are for every hour and the rotation period is 24.62 hours, each diffusion rate roughly correspond to the half of this period.

Added to the gas diffusion, there is the leakage rate, which depends on the quantity of pinholes present in the material. Furthermore, as the mission is carried out, more pinholes will appear and some of the original ones will become bigger.

Using the NCAR tabulated values (see [5]), it is possible to have an expression of the leakage rate per day in a pinhole for every pressure differential, which will be used when the new pressure differential is computed after accounting for the lost helium. This expression is:

$$\text{Leakage rate} = 1{,}4 \cdot 10^{-5} \cdot \Delta P + 0{,}001 \quad \textbf{(2.4)}$$

This leakage rate is given in terms of volume, so using the helium density it can be transformed in a mass-loss rate. Furthermore, this rate must be different for day and night, and then it has also to be applied for each half of the rotation period.

Finally, this leakage rate is for a single pinhole (0.1 mm). In order to have an estimation of the dependence of the quantity of these pinholes, the endurance of the aerobot will be computed for different values of a parameter called “pinholes distribution”, which determines the number of pinholes per square meter of balloon envelope.

According to the fact that LLDPE is a material that presents few pinholes, the lowest value will be of only 0.5 pinholes per square meter, which represents the original film at initial conditions. The highest value will be of 3 pinholes per square meter, which represents the balloon envelope well into the mission, when it has been damaged by atmospheric conditions and suspended dust.

**Table 2.10** Diffusion and leakage rate at specific float altitude at initial conditions

| Diffusion rate (kg/h) | | Leakage rate (kg/h) | |
|---|---|---|---|
| Day | Night | Day | Night |
| $3{,}535 \cdot 10^{-7}$ | $1.411 \cdot 10^{-8}$ | $2.5 \cdot 10^{-3}$ | $2.1 \cdot 10^{-3}$ |

The computation of the endurance in this project is for every rotation period, so the final result will be in days. This means that every 24.62 hours, the new pressure differential is calculated, as well as the new diffusion and leakage rates, until the internal pressure at day or night is lower than the atmospheric one. The length of the resulting vector of pressure differentials versus time determines the lifetime of the aerobot. It must be mentioned that these are Martian days (sols), so they would correspond to more days on Earth.

The results are shown in table 2.11.

**Table 2.11** The aerobot lifetime for different pinhole distributions

| Pinhole distribution (holes/m$^2$) | 0.5 | 1 | 2 | 3 |
|---|---|---|---|---|
| Aerobot endurance (sols) | 3060 | 1531 | 766 | 511 |

It is clearly proved that the leakage rate is much more influential than the gas diffusion rate, as it could also be seen in table 2.10. Furthermore, focusing on the results, these are good values for the aerobot, as it would be able to travel over Mars' surface for a long time.

## 2.4. Mission features

### 2.4.1. Deployment

This procedure is one of the most delicate processes of the mission. In some past designs, there was the idea of deploying and inflating the balloon while the system is descending in the Martian atmosphere. This is a dangerous process because there is a short and limited amount of time to perform the deployment. The huge balloon volume required to make the aerobot float adds another difficulty in the procedure.

From these statements, a ground launched balloon is a safer option. Additionally, it provides the chance of deploying a rover or any other scientific payload on the surface. The flat terrain of the northern hemisphere of Mars allows this type of deployment. Nevertheless, the system must take into account the possibility of the damage of the envelope caused by wind, dust, surrounding rocks, or even other parts of the landing system due to the large size of the balloon on ground.

The optimal ground deployment system would be the Shielded Mars Balloon Launcher (SMBL) (see [19]). It is a system created by Aurora Flight Sciences, which was awarded by NASA in 2009 to study and develop a system that accomplishes these requirements.

**Fig. 2.24** The SMBL deployment system

The SMBL consists on inflatable structures as in Fig. 2.24 that ensures a safe environment for the deployment and inflation of the balloon, although it requires a large volume. The concept proposed has only 15 kg of mass and it also takes up a small packed volume of 0.15 $m^3$ during the journey to Mars. Moreover, it can also be used as an extra scientific payload on surface.

### 2.4.2. Gondola

Considering the float altitude of the aerobot, there is a list of possible scientific instrumentation that would be useful for the exploration of Mars. Basic elements as an antenna, a transmitter, a receiver, the energy supply system like solar panels and altimeter are included in the gondola.

- CCD or CMOS cameras. These are the most commonly used in astronomical research. They could have two goals: taking pictures of the Martian surface and analysing the surface composition. This last procedure would be possible thanks to a multispectral camera with a large set of filters that would compare the pseudo-spectrum received with a spectral library of known materials to make a study of the surface constituents.

- A detector of the atmospheric composition. Recently, the Curiosity rover has discovered that atmospheric methane changes along the seasons, so its origin may come from microorganisms instead of volcanic activity. Then clearly, a methane detector could be really useful to continue this investigation.

**Fig. 2.25** The Curiosity rover

- A radiation detector in order to analyse the presence of isotopes on the surface and its radioactivity, as well as the effects of cosmic radiation.

## 2.5. Extra improvements

Up to this point, we have analysed the design of a basic aerobot composed of a single spherical balloon envelope holding the buoyant gas. In general, this design would be able to accomplish the minimum requirements of the mission, but there are some extra systems of features that could improve the aerobot performance to a greater or lesser extent.

### 2.5.1. Electric engine

As describe in the MAPS design, a propelled balloon would have a controllable track and would also gain horizontal speed. This would enlarge significantly the exploring area of the aerobot. The aerobot would then become a hybrid balloon.

The best option to propel the balloon system is by means of an electric engine that would impulse the aerobot by rotating an airscrew. The thrust given by an engine would compensate wind disturbances. The engine‘s required power would be generated by a solar panel.

This panel can be similar to the satellite’s flat ones, but, after a certain period of time, it would become useless due to the accumulated dust. From this, two other options remain. One would be a flexible leaning skirt panel hanging from the perimeter, where the dust will fall down. The other one would be the same as in MAPS mission, covering the balloon envelope with a flexible skin of photovoltaic cells. In both cases, the wind would help at cleaning the dust.

The drawbacks of this addition are the extra weight of this system, so the envelope would have to be bigger, and the complexity of designing a propeller optimized for the atmosphere of Mars as well as the flexible solar panel, which has to be resistant, light and efficient. Obviously, the solar dependence is another factor to take into account.

### 2.5.2. Gas collector and separator

Endurance is one of the most relevant parameters in the mission, so it has to be always maximized. Thanks to a scientific research group of the University of Budapest (see [20]), there is a system that significantly extends the desired aerobot lifetime.

Before commenting the system, it must be recalled that buoyant gas escapes to the outside of the envelope due to leakage and diffusion; simultaneously, carbon dioxide enters into the balloon to a lesser extent due to its bigger molecular size.

The system consists in making two envelope films instead of one, generating between them a “collector space”, and then, including between them a disjunctive separator. This separator has the mission of collecting the helium and carbon dioxide leaked through the inner and outer film respectively, cooling them until the $CO_2$ becomes liquid, separating both gases and returning them to their original location. Thanks to this process, helium would go back inside the balloon and carbon dioxide would return to the atmosphere. In this way helium loss would be notably minimized.

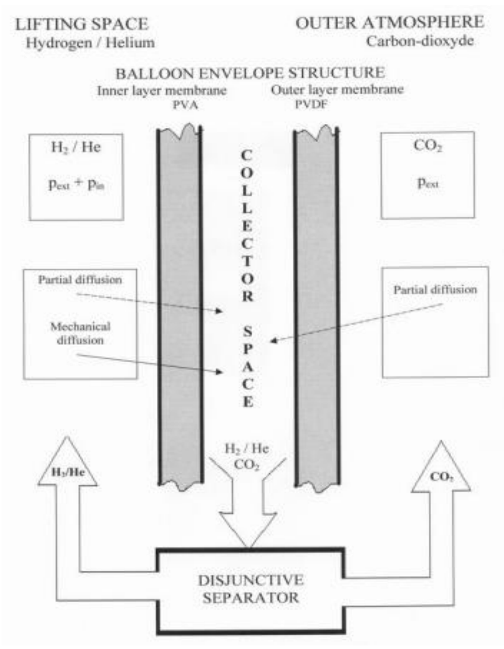



**Fig. 2.26** Multiple layer collector-separator system

The inconveniences of this system are that the disjunctive separator has to be continuously supplied by electricity, the small extra weight and the possible problems that may have the film due to the tensile strength. Both films have to be half thicker than the usual film, so the tensile strength is increased, which means that the pressure differential must be reduced. However, if the system works correctly, this does not suppose a decrease in the endurance.

### 2.5.3. Altitude control system

The basic aerobot design continuously floats at a constant altitude, but the possibility of varying the float altitude in a controlled way would improve the exploration of the planet.

GoogleX together with Raven Industries registered in 2014 and 2015 two patents of two buoyancy control methods that are nowadays used by the GoogleX SPB (see [21, 22]), and which could also be employed by a Mars aerobot. These systems use an internal bladder and a diaphragm respectively.

Both systems are composed by a balloon divided in two volumes: one volume with buoyant gas inside it and the second volume with atmospheric air. At the bottom or top of the balloon there is an altitude control system that consists in a valve that introduces or expels atmospheric air from the second volume.

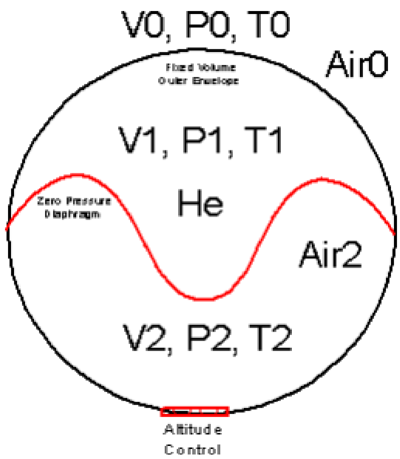



**Fig. 2.27** General diagram of the altitude control system

As the atmospheric air is denser than the helium, this variation of the second volume produces a change on the vertical position of the aerobot. If the altitude control system absorbs air, the aerobot goes down and when this air is vented off, the aerobot rises. The altitude variation depends on, and is limited by, the size of the second volume.

The trouble with this improvement is again the increase of weight and volume of the balloon, taking into account that its size is already quite big due to the properties of the Martian atmosphere. Nevertheless, the diaphragm method could be a better option because it does not need so much internal envelope as the bladder method.

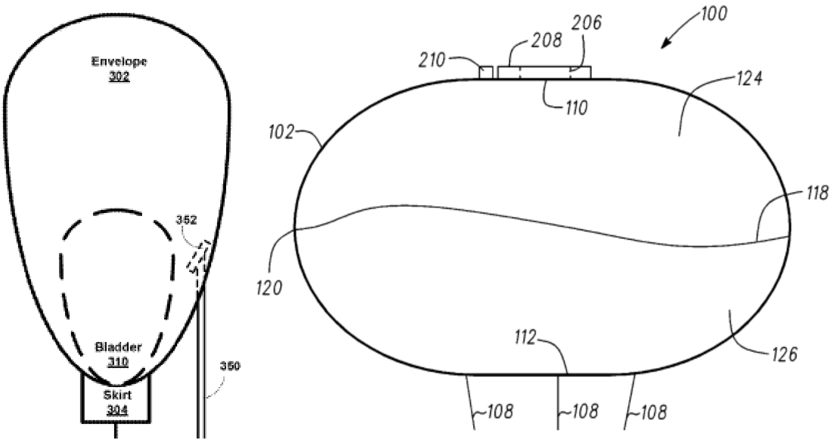



**Fig. 2.28 and 2.29** The bladder and diaphragm methods

These three improvements require a cutting-edge technology due to their complexity, so a large amount of research is mandatory to make these systems real.

# CONCLUSIONS AND FUTURE WORK

In summary, we have determined theoretical frame for aerobot flight in the atmosphere of any planet or moon, provided there exists a suitable atmospheric model. These flight features are the balloon volume and mass, gas temperature, pressure and density, differential pressure, tensile strength of the film, vertical ascension and endurance of the system.

These computations are applied to an atmosphere model and, considering planet characteristics as its topography or weather, a float altitude range is also settled.

After an analysis of the different balloon systems and buoyant gases, it has been decided that the best aerobot choice is a Super Pressure Balloon filled with helium as lifting gas and made of a LLDPE film of 38.1 microns.

Then, this aerobot model has been applied to Mars. After a study of the surface and atmosphere conditions of this planet, it was decided that the float altitude range of this aerobot would be from 6 to 12 km over the zero level of the datum. Moreover, the optimal flight altitude is 8 km from this datum’s zero level because there is no change in atmospheric air density from day to night, and so there is no variation in the float altitude during the diurnal cycles.

After these considerations, the resultant aerobot characteristics have been determined, demonstrating that an aerobot in Mars is quite larger than in Earth due to the low atmospheric air densities (a factor of 100 smaller than Earth’s). Nevertheless, its endurance is notably increased thanks to the low temperatures, making gas diffusion almost negligible. Mission lifetime dependence only falls onto pinhole leakage.

Finally, some extra systems have been proposed in order to improve the performance of the different mission features. An electric engine and an altitude control system would enlarge the exploration area in the 3 dimensions, and a gas collector and separator would increase significantly the system endurance.

The results obtained are compatible with a figure from real systems, so the design is feasible. However, this design requires an advance in balloon envelope materials due to their actual fragility and poor resistance to the generation of pinholes. Besides, the extra improvements described are currently only theoretic concepts that require a substantial development.

To conclude, the design of a planetary aerobot is feasible under the limitations imposed in this work.

# REFERENCES

**[1]** Goddard Space Flight Centre, NASA. (n.d.). *The Differences Between a Zero Pressure Balloon and a Super Pressure Balloon*. Retrieved April 19, 2018, from https://sites.wff.nasa.gov/code820/spb_differences_between_zpandspb.html

**[2]** Goddard Space Flight Centre, NASA. (n.d.). *Super Pressure Balloon Design Approach*. Retrieved April 19, 2018, from https://sites.wff.nasa.gov/code820/spb_design_approach.html

**[3]** Hall, N.. (2015). *Earth Atmosphere Model - Metric Units*. Retrieved April 24, 2018, from https://www.grc.nasa.gov/www/K-12/airplane/atmosmet.html

**[4]** IIT Research Institute of Chicago, Illinois (1 March 1968). *Permeability data for aerospace applications prepared for National Aeronautics and Space Administration*. Retrieved from https://ntrs.nasa.gov/search.jsp?R=19690004779

**[5]** Lally, V. E, NCAR, (June 1967). *Superpressure Balloons for Horizontal Soundings of the Atmosphere*. National Centre for Atmospheric Research (NCAR). Retrieved from https://opensky.ucar.edu/islandora/object/technotes%3A20/datastream/PDF/view

**[6]** Braeunig, R. A. (2014). *Basic of Space Flight: Atmospheric Models*. Retrieved May 11, 2018, from http://www.braeunig.us/space/atmmodel.htm

**[7]** NASA. (1976). *Atmosphere State Properties from Viking 1 and 2 Accelerometer Data*. Retrieved from http://www.braeunig.us/space/pdf/vikingdata.txt

**[8]** Williams, D. R. (2016). *Mars Fact Sheet*. Goddard Space Flight Centre, NASA. Retrieved from https://nssdc.gsfc.nasa.gov/planetary/factsheet/marsfact.html

**[9]** Knight, S. (2015). *Planetary Energy Budgets.* Retrieved May 11, 2018, from https://www.scienceinschool.org/content/planetary-energy-budgets

**[10]** Blamont, J., “Planetary balloons”, *Experimental Astronomy* 22 (1–2), 21–29 (2008). DOI: 10.1007/s10686-008-9095-8.

**[11]** Nock, K. T., Balaram, J., Heun, M. K., Smith, I. S., & Gamber, T.. “Mars 2001 Aerobot/Balloon System Overview”. *International Balloon Technology Conference, Balloon Systems Conferences.* (1997) DOI: 10.2514/6.1997-1447.

**[12]** Pankine, A. A., Aaron, K. M., Barnes, N. C., & Nock, K. T. (January 2006). *Guided mars balloon platforms*. Retrieved from https://pdfs.semanticscholar.org/8b2c/f0e4f0f98bcebcba759ad0c8a196420b38fa.pdf

**[13]** Steinkraus, J. M., Wright, M. W., Rheingans, B. E., Steinfeld, D. E., George, W. P., Aljabri, A., Hall, J. L., Scott, D. C.. "Mars Airborne Prospecting Spectrometer". *Concepts and Approaches for Mars Exploration, Lunar and Planetary Institute,* #4307, (June 2012). Retrieved from https://www.lpi.usra.edu/meetings/marsconcepts2012/pdf/4307.pdf

**[14]** Jones, J. A., Cutts, J. A., Hall, J. L., Wu, J., Fairbrother, D. A., & Lachenmeier, T. (June 2005). *Montgolfiere balloon missions for Mars and Titan*. Retrieved from https://ntrs.nasa.gov/search.jsp?R=20060043467

**[15]** Jones, J. A., Jeng, J. "Solar Montgolfiere balloons for Mars". *International Balloon Technology Conference, Balloon Systems Conferences*. (1999). DOI: 10.2514/6.1999-3852

**[16]** Soler, J. D., Ade, P. R., Angilè, F. E., Benton, S. J., Devlin, I. J., Dober, B., … Ward-Thompson, D.. "Thermal design and performance of the balloon-borne large aperture submillimetre telescope for polarimetry BLASTPol". *Proc. SPIE* 9145 (914534), 7, (22 July 2014). DOI: 10.1117/12.2055431.

**[17]** Nagai, H.. "Characteristics of Low-Reynolds Number Airfoils in a Mars Wind Tunnel", *51st AIAA Aerospace Sciences Meeting including the New Horizons Forum and Aerospace Exposition, Aerospace Sciences Meetings.* (January 2013). DOI: 10.2514/6.2013-73.

**[18]** Hall, N. (2015). *Drag of a Sphere*. Retrieved May 28, 2018, from https://www.grc.nasa.gov/www/K-12/airplane/dragsphere.html

**[19]** Aurora Flight Sciences Corporation. (2009). *Aurora Awarded Contract by NASA to Study Balloon Launches from the Surface of Mars.* Retrieved from http://www.aurora.aero/wp-content/uploads/2017/10/APR-227_NASA-SBIR-SMBL-release-vfinal.pdf

**[20]** Nehéz, I., Bérczi, Sz., Varga, T., Darányi, I., Cseh, R., "theoretical questions of the application of the light and long life gas balloons in Martian and planetary atmospheres". *Lunar and Planetary Science XXXVII Conference, Lunar and Planetary Institute,* #1703 (March 2006). Retrieved from https://www.researchgate.net/publication/252196582_Theoretical_Questions_of_the_Application_of_the_Light_and_Long_Life_Gas_Balloons_in_Martian_and_Planetary_Atmospheres

**[21]** DeVaul, R. W., Teller, E., Biffle, C. L., Weaver, J.. (20 February 2014). "Balloon power sources with a buoyancy trade-off". *U.S. Patent No. 0048646 (A1).*

**[22]** Smith, M., Sehnert, K., Scott, R., Marsh, J. L., West, M. L.. (24 November 2015). "High altitude balloon system". *U.S. Patent No. 9,193,480 (B2).*

Escola d'Enginyeria de Telecomunicació i Aeroespacial de Castelldefels
UNIVERSITAT POLITÈCNICA DE CATALUNYA

# ANNEXES

**DESIGN OF A PLANETARY AEROBOT**

**TITULACIÓ: Grau en Enginyeria d'Aeronavegació**

**AUTOR: Álvaro Boix Candil**

**DIRECTOR: Jordi Gutiérrez Cabello**

**DATA: 15 de juliol del 2018**

# Annex A: Matlab code of the computations

## Atmosphere model Viking-Pathfinder

```
Ra=191.181; %Atmospheric gas constant (m^2/K*s^2)
po=610.5; %Atmospheric pressure (Pa)
po_night=610.5; %Atmospheric pressure at night (Pa)
To=234.8; %Surface temperature (K)
To_night=205; %Surface temperature at night (K)
go=3.7233; %Surface gravity (m/s^2)
Rp=3389510; %Planet radius (m)
e=2.7183;
hmax=12000; %Maximum aerobot height from datum (m)
h_elev=3600; %Depth elevation of the landing site (m)

h=1;
while(h<hmax+h_elev+1)
    g(h)=go*(Rp/(Rp+h))^2; %Gravity
    T(h)=To-0.0018*h; %Temperature at day
    p(h)=po*(To/T(h))^(go/(Ra*(-0.0018))); %Pressure at day
    if(h<=8500+h_elev) %First stage
        T_night(h)=To_night-0.002*h; %Temperature at night
        p_night(h)=po_night*(To_night/T_night(h))^(go/(Ra*(-0.002)));
        %Pressure at night
    elseif(h>8500+h_elev) %Second stage
        T_night(h)=164.65+0.0019*(h-h_elev); %Temperature at night
        p_night(h)=p_night(8500+h_elev)*(T_night(8500+h_elev)/T_night(h))^(go/
        (Ra*0.0019)); %Pressure at night
    end
    rhoa(h)=p(h)/(Ra*T(h)); %Air density at day
    rhoa_night(h)=p_night(h)/(Ra*T_night(h)); %Air density at night
    h=h+1;
end
```

**Balloon computations**

**Constants**

```
cd=0.5; %Drag coefficient at Reynolds 10^(-3)
MMhe=4.003*10^(-3); %Helium molar mass (kg/mol)
Rconst=8.315684; %Ideal gas constant (J/K*mol)
Rhe=Rconst/MMhe; %Helium ideal gas constant (J/K*kg)
rholldp=926; %LLD Polyethylene film density (kg/m^3)
tsult=3*10^7; %LLD Polyethylene film ultimate tensile stress (Pa)
sigma=5.67*10^(-8); %Stefan-Boltzmann constant
```

**Parameters**

```
fl=8000; %Specific float altitude from datum (m)
th=38.1*10^(-6); %LLD Polyethylene film thickness (m)
mpl=10; %Payload mass (kg)
abs=0.016; %Absorbance
em=0.05; %Emissivity
alb=0.25; %Planet albedo
flux_s=586.2; %Solar energy flux (W/m^2)
flux_m=110; %Mars' energy flux (W/m^2)
```

**Gas temperature**

```
h=1;
while(h<hmax+h_elev+1)
    Tgas(h)=(((abs*(flux_s+alb*flux_s)+em*flux_m)/(em*4*sigma))+T(h)^4)^(1/4);
    %Gas temperature at every altitude
    Tgas_night(h)=((em*flux_m+em*4*sigma*T_night(h)^4)/(em*4*sigma))^(1/4);
    %Gas temperature at night
    h=h+1;
end

Tgas_fl=Tgas(fl+h_elev); %At specific altitude
Tgas_night_fl=Tgas_night(fl+h_elev);
```

**Pressure differential**

```
h=1;
dif_pres_night=70; %Differential pressure at night
while(h<hmax+h_elev+1)
    p_int_night(h)=p_night(h)+dif_pres_night; %Gas pressure at night
    rhohe_b(h)=p_int_night(h)/(Rhe*Tgas_night(h)); %Gas density at float
    altitude
    p_int_b(h)=rhohe_b(h)*Rhe*Tgas(h); %Pressure difference condition
    dif_p(h)=p_int_b(h)-p(h); %Differential pressure at day
    h=h+1;
end

p_int_b_fl=p_int_b(fl+h_elev);
rhohe_b_fl=rhohe_b(fl+h_elev);
p_int_night_fl=p_int_night(fl+h_elev);
dif_pres=dif_p(fl+h_elev);
```

**Gas pressure and density during ascension**

```
h=1;
while(h<fl+h_elev+1)
    p_int(h)=p(h)+dif_pres; %Gas pressure at every altitude during ascension
    rhohe(h)=p_int(h)/(Rhe*Tgas(h)); %Gas density at every altitude during
    ascension
    h=h+1;
end
```

**Maximum radius and masses for every float altitude**

```
h=1;
while(h<hmax+h_elev+1)
    x=[(4/3)*pi*((rhoa(h))-rhohe_b(h)) -4*pi*th*rholldp 0 -mpl]; %Equalising
    buoyancy and weight
    radius=roots(x);
    rad_max(h)=radius(1); %Maximum radius
    Vb_max(h)=(4/3)*pi*rad_max(h)^3; %Maximum volume
    mhe(h)=Vb_max(h)*rhohe_b(h); %Gas mass
    Scover(h)=4*pi*rad_max(h)^2; %Cover surface
    mcover(h)=Scover(h)*th*rholldp; %Cover mass
    mdry(h)=mcover(h)+mpl; %Dry mass
    mtotal(h)=mhe(h)+mdry(h); %Total mass
    h=h+1;
end

rad_max_fl=rad_max(fl+h_elev); %Maximum radius
Vb_max_fl=(4/3)*pi*rad_max(fl+h_elev)^3; %Maximum volume
```

**Balloon masses and surface**

```
mhe_fl=mhe(fl+h_elev); %Gas mass
Scover_fl=Scover(fl+h_elev); %Cover surface
mcover_fl=mcover(fl+h_elev); %Cover mass
mdry_fl=mdry(fl+h_elev); %Dry mass
mtotal_fl=mtotal(fl+h_elev); %Total mass
```

**Tensile stress**

```
h=1;
while(h<hmax+h_elev+1)
    s_tens_max(h)=dif_p(h)*rad_max(h)/2; %Surface tension
    tens_max(h)=s_tens_max(h)*2*pi*rad_max(h); %Maximum tension
    ts_max(h)=tens_max(h)/(2*pi*rad_max(h)*th); %Tensile strength
    h=h+1;
end

s_tens_max_fl=dif_pres*rad_max(fl+h_elev)/2;
tens_max_fl=s_tens_max_fl*2*pi*rad_max(fl+h_elev);
ts_max_fl=tens_max_fl/(2*pi*rad_max(fl+h_elev)*th);
```

**Radius and vertical speed during ascension**

```
h=1;
while(h<fl+h_elev+1)
```

```
    Vb(h)=mhe(fl+h_elev)/rhohe(h); %Volume at every altitude
    rad(h)=(3*Vb(h)/(4*pi))^(1/3); %Radius at every altitude
    rho_av(h)=mtotal(fl+h_elev)/Vb(h); %Average density at every altitude
    fbuo(h)=(rhoa(h)-rho_av(h))*Vb(h)*g(h); %Buoyancy force
    wei(h)=mtotal(fl+h_elev)*g(h); %Weight force
    v(h)=real(sqrt(2*(fbuo(h))/(rhoa(h)*cd*pi*rad(h)^2))); %Vertical speed of
    the balloon
    h=h+1;
end
```

**Time to reach float altitude**

```
h=1;
time=1;
k=1;
while(h<fl+h_elev+1)
    vel(time)=v(h); %Vertical speed at every second
    if(vel(time)<1)
        vel(time)=1;
    end
    height_v(k)=fix(h+vel(time)); %Altitude at every second
    h=height_v(k);
    k=k+1;
    time=time+1;
end

time_to_fl=length(vel); %Time spent to reach float altitude in seconds
```

**Gas diffusion**

```
perm_fl_day=3.382*10^(-14); %Permeability a float altitude at daylight (-30°C)
diff_rate_vol_fl_day=perm_fl_day*Scover_fl*dif_pres/th; %Diffusion rate of
volume at daylight
diff_rate_m_fl_day=diff_rate_vol_fl_day*rhohe(fl+h_elev); %Diffusion rate of
mass at daylight

perm_fl_night=1.35*10^(-15); %Permeability a float altitude at night (-70°C)
diff_rate_vol_fl_night=perm_fl_night*Scover_fl*dif_pres/th; %Diffusion rate of
volume at night
diff_rate_m_fl_night=diff_rate_vol_fl_night*rhohe(fl+h_elev); %Diffusion rate
of mass at night
```

**Gas leakage and endurance**

```
day=1;

p_int_diff(1)=p_int(fl+h_elev);
p_int_night_diff(1)=p_int_night(fl+h_elev);
diff_rate_m_day(1)=diff_rate_m_fl_day;
diff_rate_m_night(1)=diff_rate_m_fl_night;
dif_p_diff(1)=dif_pres;
dif_p_night_diff(1)=dif_pres_night;
mhe_diff(1)=mhe_fl;
rhohe_diff(1)=rhohe(fl+h_elev);
leak_rate_day(1)=0;
leak_rate_night(1)=0;
```

```
holes_meter=0.5; %Number of pinholes (0.0001 m of size) per square meter
holes=holes_meter*Scover_fl; %Total number of pinholes

while(p(fl+h_elev)<=p_int_diff(day) &&
p_night(fl+h_elev)<=p_int_night_diff(day))

    leak_rate_day(day+1)=(1.4*10^(-5)*dif_p_diff(day)+0.001)*rhohe_diff(day)
    *holes*(24.62/24)*0.5; %Leakage rate at every day

    leak_rate_night(day+1)=(1.4*10^(-5)*dif_p_night_diff(day)+0.001)
    *rhohe_diff(day)*holes*(24.62/24)*0.5; %Leakage rate at every night

    mhe_diff(day+1)=mhe_diff(day)-diff_rate_m_day(day)*12.31-
    diff_rate_m_night(day)*12.31-leak_rate_day(day+1)-leak_rate_night(day+1);
    %Gas mass at every day

    rhohe_diff(day+1)=mhe_diff(day+1)/Vb_max_fl; %Gas density at every day

    p_int_diff(day+1)=rhohe_diff(day+1)*Rhe*Tgas(fl+h_elev); %Gas pressure at
    every day

    p_int_night_diff(day+1)=rhohe_diff(day+1)*Rhe*Tgas_night(fl+h_elev); %Gas
    pressure at every night

    dif_p_diff(day+1)=p_int_diff(day)-p(fl+h_elev); %Pressure differential at
    every day

    dif_p_night_diff(day+1)=p_int_night_diff(day)-p_night(fl+h_elev);
    %Pressure differential at every night

    diff_rate_m_day(day+1)=perm_fl_day*Scover_fl*dif_p_diff(day+1)*rhohe_diff(
    day+1)/th; %Mass loss at every daytime

    diff_rate_m_night(day+1)=perm_fl_night*Scover_fl*dif_p_night_diff(day+1)*r
    hohe_diff(day+1)/th; %Mass loss at every night

    day=day+1;
end

Endurance=length(p_int_diff); %Lifetime of the balloon in days
```